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OPTIMAL RELEASE SEQUENCES FOR WATER QUALITY CONTROL IN MULTIPLE-RESERVOIR SYSTEMS

Norbert Antone Jaworski

Federal Water Pollution Control Administration
Charlottesville, Virginia

1968

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OPTIMAL RELEASE SEQUENCES FOR WATER QUALITY CONTROL IN MULTIPLE-RESERVOIR SYSTEMS

by

Norbert Antone Jaworski

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1968

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CHAPTER I

INTRODUCTION

To better control, protect, and manage the water quality of our rivers, water resources engineers have directed increased attention to development of analytical techniques for determination of procedures and policies by which optimal operation and management of entire river basins may be realized. Analytical approaches to the design and management of water resources systems have as their fundamental objective the provision of water at a pre-set quality for the least cost. The analyses also include investigation of alternatives, determination of inadequacy probabilities, and establishment of optimal operational procedures.

There are essentially three methods for controlling water quality within a given river basin:

1. Regulation of the total waste load. This approach requires establishment of specifications for the degree of treatment of wastewaters to be effected prior to discharge, or, in the case of some industrial processes, for certain in-plant modifications or process changes.
2. Regulation of river flow, either by reservoirs, pumping from well fields, or by pumped storage, in order to provide appropriate dilution of waste loads when required.
3. Installation of in-stream treatment devices which either provide an integral means for removal of pollutants or which act to enhance the rate of natural removal of pollutants; stream aerators, for example, function in the latter capacity.

The engineering approach to analysis and solution of water quality control problems is greatly influenced by the degree of river basin development. Two general types of situations which are encountered in the regulation of flow for quality control are:

1. Operational Situation

   For a river basin in which the reservoir system is fully developed, the problem is one of determining that flow release sequence which will provide best quality for a given probability of inadequacy. Other water requirements may or may not be included in the approach.

2. Design and Operational Situation

   For a basin in which flow regulation possibilities are either limited or nonexistent, but for which reservoir development is proposed, the problem becomes one of making decisions regarding both design and operation. Not only must storage requirements for quality control be determined, but also a flow release sequence to meet the prescribed quality control criteria for a given probability of inadequacy must be established.

The two problems are closely related, although the data required for proper design are usually less readily available than that needed for establishing operational patterns. Many parameters cannot be rigidly defined, and thus often are not included in reservoir design for quality control. The problem is further complicated by the dependence of the operational pattern on the proposed storage requirements and possible operating sequences.

The purposes of the present study have been to:

1. develop a method for determination of an optimal flow regulation sequence for quality control from multiple reservoir sites;

2. investigate various physical, biochemical, engineering design, and socio-economic parameters which may influence the optimal flow release sequence;
3. demonstrate the response sensitivity of the method to these parameters in an actual basin; and
4. investigate the significance of various definitions of optimal such as "best" quality, minimum flow, and least-cost on the reservoir release sequences.

Chapter II presents a brief review of the literature pertaining to formulations and relationships for description of water quality transformations and for determining flow regulation and wastewater treatment requirements. Included in the review are models which have been proposed or are currently being used in the area of water pollution control for least-cost solutions for wastewater treatment, flow regulation, estuary analysis, and generation of synthetic hydrology.

Chapter III is devoted primarily to development of the flow release model. The basic concepts of the model and the development of the descriptive paragon are presented. A brief description of the Patuxent and Potomac River Basin Systems which were used as test basins for the model are presented in Chapter IV.

In Chapter V, the development and interpretation of the incremental-flow and the dynamic-programming tableaux are explained. Formulation of flow release patterns is presented in the latter part of Chapter V.

Chapter VI is devoted to a sensitivity analysis of certain physical, biochemical, engineering design, and socio-economic parameters.

Various adaptations of the flow release model, including that providing for least-cost solution, are presented in Chapter VII. A comparison is made of the reservoir release sequence as developed using various optimization parameters. Other possible model expansions are proposed, including river basin water quality simulation with linkage to estuarine models.

In Chapter VIII, the results of the flow release model are discussed. The summary and conclusions of the study are presented in Chapter IX.

Some typical problems and possible solutions encountered in model verification are presented in Appendix A. A proposed model for predicting phosphate concentration in flowing streams is also presented therein.

Detailed schematics of the Potomac River Basin showing wastewater discharges, dams, water intakes, etc. are exhibited in Appendix B, along with the basic inventory and stream flow data used in the flow release model.

Data formats, array notation and a brief description of the use of the verification link and flow release model are contained in Appendix C. The computer programs for the verification link and flow release model are given in Appendices D and E, respectively.

CHAPTER II

REVIEW OF LITERATURE

Before one can attempt to evaluate the effects of wastewater discharge or flow regulation on water quality in a stream, it is necessary to understand the relationships between the geophysical characteristics of the drainage area and the biochemical and physical environment of the stream. The first part of this chapter presents the historical development of the relationships between dissolved oxygen (DO), biochemical oxygen demand (BOD), stream flow, temperature, velocity, depth, and certain other parameters which may affect water quality. The basic quality parameters considered in this study are DO, BOD, and temperature. The latter part of the chapter presents various models which are currently being used for determining treatment requirements and flow regulation policies.

WATER QUALITY FORMULATIONS

The first quantitative description of deoxygenation and reaeration relationships in streams was presented in the classical studies of Streeter and Phelps[1] in 1925. These authors noted that the net rate of change ($\frac{dD}{dt}$) in the oxygen deficit (D) in a stream at any time was equal to the algebraic sum of the opposing rates of deoxygenation and reaeration. This is expressed mathematically as:

$$\frac{dD}{dt} = K_1L - K_2D \qquad ----- (2\text{-}1)$$

in which

K_1 = Rate coefficient for deoxygenation, reflects the availability of organic matter and the activity of the organisms present

L = Oxygen demand of the organic matter, in mg/l

K_2 = Rate coefficient for reaeration, reflects the degree of turbulence and the transfer-efficiency at the air-water interface

D = Dissolved oxygen deficit of the water in mg/l

The expression given by Streeter and Phelps is a linear differential equation of the first order. The first term, K_1L, expresses the rate of oxygen utilization or deaeration resulting from oxidation of organic waste matter. The term K_2D is the rate of reaeration, which is a function of the difference between the dissolved oxygen concentration at any time and the concentration corresponding to a condition of oxygen saturation.

Streeter and Phelps further stated that "The rate of biochemical oxidation of organic matter is proportional to the remaining concentration of the unoxidized substance, measured in terms of oxidizability." This can be expressed mathematically as a first order reaction with the integrated form

$$L_t = L_a e^{-K_1 t} \qquad \text{- - - - - (2-2)}$$

in which

L_a = The initial concentration of oxidizable organic matter, or ultimate BOD

L_t = The concentration of oxidizable organic matter at time (t)

t = Time elapsed, in days

The integrated form of the Streeter-Phelps linear differential equation for $\frac{dD}{dt}$ defines the dissolved oxygen deficit, D_t, at any time in terms K_1, K_2, L_a, and the initial deficit, D_a, as

$$D_t = \frac{K_1 L_a}{K_2 - K_1} \left(e^{-K_1 t} - e^{-K_2 t}\right) + D_a e^{-K_2 t} \quad \text{- - - - - (2-3)}$$

In their studies of the Ohio River, Streeter and Phelps also investigated the effect of temperature on the deoxygenation and the reaeration coefficients and formulated appropriate empirical relationships. The basic formulation for the effect of temperatures on the deoxygenation rate coefficient is

$$\frac{K'}{K} = \theta^{(T' - T)} \quad \text{- - - - - (2-4)}$$

where T' and T are two known temperatures, K' and K are the corresponding values of the deoxygenation coefficient, and θ is the thermal coefficient, a constant for the reaction.

The reaction rate constant for reaeration was determined experimentally for the Ohio River, and was found to vary with flow and depth according to the relationship

$$K_2 = \frac{C\,V^n}{H} \quad \text{- - - - - (2-5)}$$

in which

V = Velocity of flow in feet/sec

H = Mean river depth in feet

C = Empirical constant

n = Empirical exponent

The original formulation proposed by Streeter and Phelps has been expanded over the years. However, the dissolved oxygen and BOD formulations, temperature corrections, and reaeration formulation have held true with slight modifications.

In 1939, Fair[2] simplified the use of the oxygen sag relationship developed by Streeter and Phelps. Fair introduced a new constant called the Self-Purification Factor, "f".

$$f = \frac{K_2}{K_1} \qquad \text{- - - - - (2-6)}$$

By setting $\frac{dD}{dt} = 0$ in Equation 2-1, one then obtains

$$L = \frac{K_2}{K_1} D \qquad \text{- - - - - (2-7)}$$

By solving for the critical deficit, D_c, and incorporating the "f" factor

$$D_c = L_a (f)^{\frac{f}{1-f}} \qquad \text{- - - - - (2-8)}$$

where D_c is the maximum dissolved oxygen deficit at the critical deficit point, in mg/l.

To further facilitate the use of the oxygen sag equation, Fair developed a nomogram and a table of "f" values for various types of streams. The use of this equation eliminates the need for determining a separate reaeration coefficient. However, it must be recognized that the formulation is based on the assumptions that the reach is homogeneous. The use of this self-purification factor is quite popular today, primarily for rough evaluation or approximation.

In 1948, Thomas[3] expanded the oxygen sag relationship to include a third term, K_3. The factor K_3 was used to reflect the composition of the waste and receiving water and the relative quiescence of the stream at the point of interest.

The equation developed by Thomas has the form

$$D_t = \frac{L_a K_1}{K_2-(K_1+K_3)} \left[e^{-(K_1 + K_3)t} - e^{-K_2 t} \right] + D_a e^{-K_2 t} \quad \text{- - - - (2-9)}$$

in which K_3 is a constant of proportionality reflecting the composition of the waste and receiving stream, and the quiescence of the stream.

Thomas indicated that the time-average value of K_3 is zero, with fluctuations occurring with changes in temperature, flow, and channel conditions. The range of values of K_3 given by Thomas was -0.36 and +0.36. Thomas also developed a nomogram for the solution of the expanded equation.

Another variation of the oxygen sag equation for establishing oxygen relationships in streams was proposed by Velz[4,5,6,7]. This variation, called the "Oxygen Budget," is an accounting stepwise method for determining oxygen balance.

On the asset side of the accounting ledger, Velz includes dissolved oxygen present in the stream, that provided by reaeration, and that contributed by photosynthetic activity. On the liability side of the ledger, Velz includes exertion of the BOD, demand of sludge deposits, biological extraction, etc. The DO deficit is calculated for a given reach and stream flow by summing the sources and sinks of oxygen and applying proper conversion factors.

In 1961, Thomas[8] simplified the oxygen sag relationship and made it more amenable to stream sampling data. An approximate solution to the basic linear differential equation proposed by Streeter and Phelps was developed. The equation for the approximate solution or "step-method" of Thomas is

$$D_t = Y_t e^{-K_2 t/2} + e^{-K_2 t} D_a \qquad \text{- - - - - (2-10)}$$

in which Y_t is the oxygen uptake in the reach, mg/l or #/day, and all other terms are as previously defined. The principal advantage of the step method is that only 5-day BOD analyses need to be determined. The time-consuming deoxygenation coefficient (K_1) and ultimate BOD (L_a) analyses are not required.

Thomas developed nomograms to reduce the number of calculations required to determine the necessary coefficients and constants. Once approximate values of K_1 and K_2 are obtained from statistical analysis by interpolation and extrapolation of observed stream survey data, the equation can then be used to determine the oxygen balance in the stream at different stream conditions, loadings or temperatures.

In order to more realistically represent the BOD reaction in the stream, Thomas proposed using a second-order formulation rather than the first-order formulation of Streeter and Phelps. This can easily be incorporated into the step method and the nomograms are also available for its solution.

The step method as originally proposed by Thomas does not include any benthic or photosynthetic components; however, these can be readily added to the equation. The approximate solution is accurate if the change in deficit is kept to less than 3 mg/l within a section.

In considering the stabilization of organic matter in a natural stream, O'Connor[9] distinguishes between factors that affect the overall removal of oxygen-utilizing material and those that affect the direct oxidation of organic material. The total rate of removal is expressed by the coefficient "K_r", while the rate of oxidation is described by the coefficient "K_d". The coefficients "K_d" and "K_r" may be quite different from that determined in the standard laboratory BOD test "K_1". This is primarily due to the difference in physical and chemical characteristics of the laboratory and stream environments.

The relationship for the oxygen balance in the stream as proposed by O'Connor is

$$D_t = \frac{K_d L_a}{K_2 - K_r}\left[e^{-K_r t} - e^{-K_2 t}\right] + D_a e^{-K_2 t} \qquad ---- (2\text{-}11)$$

The above equation, which is similar to the formulation developed by Thomas, also provides for factors like biological extraction and sludge deposits as proposed by Velz.

A time-dependent dissolved oxygen sag relationship, developed by Li[10], incorporates non-uniform stream channel cross sections and temporal variations of BOD and DO in the wastewaters. Li obtained the following equation for the oxygen sag

$$D_t = e^{-K_2 t}\left[C_s - F(\xi) + f(\xi)\int \frac{1}{v} K_1 e^{(K_2 - K_1)t}\, dx\right] \qquad ---- (2\text{-}12)$$

where $t(x) = \int \frac{dx}{V}$ is the time of travel from cutfall to point x

V = Velocity of stream flow

C = Saturation value of DO

$F(\xi)$ = DO of stream at waste outfall

$f(\xi)$ = BOD of stream at waste outfall

ξ = Variable time element indicating the net effect of time of day and travel time downstream.

The non-uniform channel aspect investigated by Li is important. However, modern high-speed computers permit the incorporation of many small streams in the basic formulation, thus reducing the significance of the non-uniform channel solution given by Li. The temporal fluctuations in an effluent can be significant in some areas, especially for industrial waste discharges.

Frankel[11,12] expanded the formulations of Li and developed a dynamic oxygen sag analysis which also incorporates photosynthetic effects. A coliform and detergent model was also advanced by Frankel.

Expanded BOD and DO formulations which include the effects of sedimentation, absorption, additions of BOD along the stretch of a stream, removal of oxygen by benthal demand or plant respiration, and the addition of oxygen by photosynthesis have been developed by Dobbins[13,14]. The equation for the dissolved oxygen profile as proposed by Dobbins is given below:

$$D_t = \frac{K_1 \left[L_a - \frac{L_A}{K_1 + K_3}\right] \left[e^{-(K_1 + K_3)t} - e^{-K_2 t}\right]}{K_2 - (K_1 + K_3)} + D_a e^{-K_2 t} + \left[\frac{D_b}{K_2} + \frac{K_1 L_A}{K_2(K_1 + K_3)}\right] (1 - e^{-K_2 t}) \quad \text{- - - - - (2-13)}$$

where

D_b = Denotes the net rate of oxygen removal by benthal demand and the effects of plants

L_A = Rate of addition of BOD along the reach

The other terms in the equation are similar to those in the previous equations.

Dobbins also investigated the effect of longitudinal dispersion on BOD and DO profiles, and concluded that the effect is negligible in most fresh-water streams.

In field surveys of the Truckee River, O'Connell, et al.[15,16], measured the effects of benthic algae and other attached plants. A modified form of the oxygen relationship which includes the net oxygen change caused by aquatic plants was used successfully for predicting daily minimum DO concentrations in the Truckee River. The DO concentrations were calculated using the following expression:

$$D_t = \frac{K_1 L_a}{K_2 - K_1} \left(e^{-K_1 t} - e^{-K_2 t}\right) - \frac{(P-R)}{K_2} \left(1 - e^{-K_2 t}\right) + D_a e^{-K_2 t} \quad \text{- - -(2-14)}$$

where (P-R) is the net contribution (photosynthesis minus respiration) and all other terms are as previously defined.

O'Connell and Thomas concluded that the oxygen produced by the algae and other attached plants generally has little net effect on the oxygen balance of a stream. However, nighttime respiration may add a large oxygen demand.

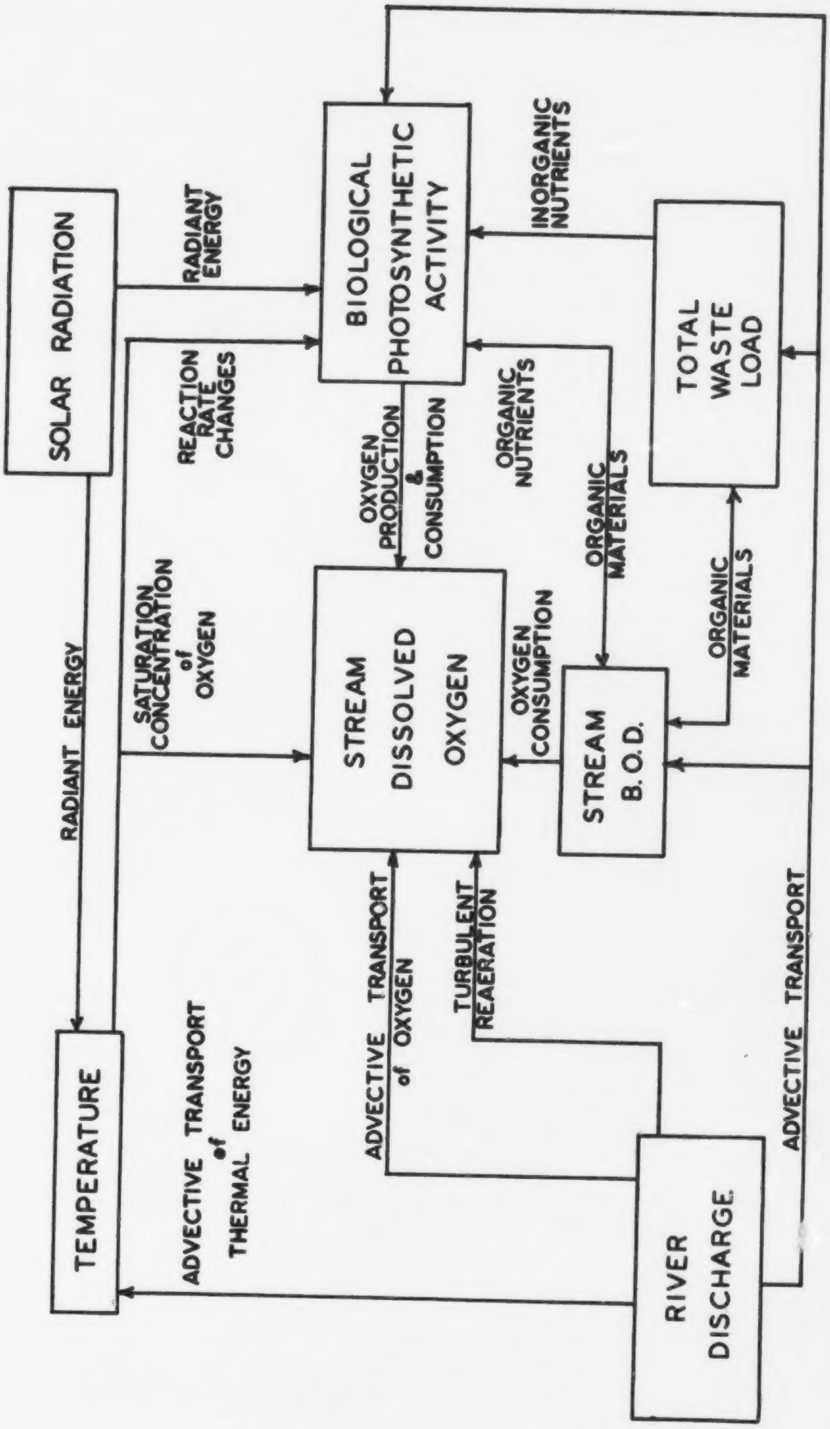
In a study of the Merrimack River, Camp[17] developed an oxygen balance formulation which included the addition of BOD from bottom deposits, removal of BOD by settling, DO production by photosynthesis, and the effects of longitudinal mixing by tides. Camp reported that the amount of DO supplied by photosynthetic activity in the Merrimack River is considerably higher than that by atmospheric reaeration, and that BOD removal by settling is greater than that by oxidation.

A general form which describes the temporal and spatial distribution of either a conservative or a non-conservative substance in a one-dimensional stream has been described by O'Connor[18] as follows:

$$\frac{\partial c}{\partial t} = \frac{1}{A_{(x,t)}} \frac{\partial}{\partial x} \left(Q_{(x,t)}\, c\right) \pm \Sigma^{S}{}_{(c,x,t)} \qquad \text{- - - - - - (2-15)}$$

in which c is the concentration of a substance of interest, A is the cross-sectional area of the stream, Q is the flow rate, and S represents the appropriate sources and sinks. The above formulation accounts for variations in the fresh-water flow and cross-sectional area, various sources and sinks of oxygen, natural and artificial reaeration, the photosynthetic contribution, bacterial and algal respiration, carbonatious and nitrogenous oxidation, and benthic deposits.

Thus, the formulation for oxygen balance in a stream originally proposed by Streeter and Phelps has evolved gradually into the more elaborate relationship given by O'Connor. A schematic summary of factors which affect the dissolved oxygen content of a stream is shown in Figure 1.


SOLAR RADIATION
RADIANT ENERGY
BIOLOGICAL PHOTOSYNTHETIC ACTIVITY
INORGANIC NUTRIENTS
TOTAL WASTE LOAD
REACTION RATE CHANGES
OXYGEN PRODUCTION & CONSUMPTION
ORGANIC NUTRIENTS
ORGANIC MATERIALS
RADIANT ENERGY
SATURATION CONCENTRATION of OXYGEN
STREAM DISSOLVED OXYGEN
OXYGEN CONSUMPTION
STREAM B.O.D.
ORGANIC MATERIALS
TEMPERATURE
ADVECTIVE TRANSPORT of THERMAL ENERGY
ADVECTIVE TRANSPORT of OXYGEN
TURBULENT REAERATION
ADVECTIVE TRANSPORT
RIVER DISCHARGE

FACTORS AFFECTING STREAM DISSOLVED OXYGEN IN A NON-TIDAL SYSTEM

Figure 1

One of the major challenges facing the water resource engineer today is the selection and implementation of a quality algorithm or model which is best suited for a particular application. Judgments have to be made regarding the significance of various parameters in a particular situation. For example, an untreated waste discharge may currently be resulting in deposition of a sludge bed in a particular section of stream; if the waste is treated, will the sludge bed be a significant parameter in the BOD and DO formulations?

Another problem associated with the implementations of a quality algorithm is the lack of systematically collected data. One of the most important contributions of the systematic approach to water resource problems has been to point out the need for well-planned field studies.

MATHEMATICAL MODELS AND METHODS FOR ANALYSIS

This section presents a review of the current literature on mathematical methods and models commonly used in water resources for analysis and control of pollution. For ease of presentation, the developments have been grouped into four categories. These are:

1. descriptive analysis;
2. statistical models;
3. river flow simulation; and
4. basin management models.

Descriptive Analysis

A descriptive analysis provides for mathematical representation of a process or processes by algorithms such as the "oxygen sag" relationship. The analysis is non-statistical and non-optimal seeking.

This type of analysis is used primarily to demonstrate cause and effect relationships of various parameters. A descriptive algorithm may be an integral part of another type of analysis, as discussed later in this chapter.

The computer programming of the "oxygen budget" by Gannon and Down[19] and the dynamic "oxygen sag" model as developed by Frankel[11] are examples of descriptive analysis for non-tidal waters. Thomann's[20] segmented and O'Connor's[21] estuary models are two examples of descriptive analysis for estuarine waters.

Statistical Models

Interpretation of observed data can often be measurably improved by use of statistical models. Graybill[22] suggests a three-step approach to the use of statistical models:

1. selection of a model to represent the physical situation;
2. mathematical treatment of the model to obtain information about the various components; and,
3. use of the model to make decisions regarding the physical situation.

Various statistical models have been used for predicting water pollution control needs. In 1950, LeBosquet and Tsivoglu[23,24] used a simple regression analysis to relate dissolved oxygen deficit to stream flow. This relationship provides a simplified approach to calculation of permissible BOD loadings for a given reach of stream.

In 1956, Churchill and Buckingham[25] presented a multiple-regression method for determining BOD loadings. In this analysis, dissolved oxygen was related to the BOD in the stream, the stream temperature, and the stream flow. The Churchill-Buckingham method was used by the Virginia State Water Control Board for estimation of the assimilation capacity of the Chickahominy River[26]. Okun, *et al.*[27], also reported the use of multiple-regression techniques for analysis of non-tidal waters. Wolman and Geyer[28], and more recently Durum and Langbein[29], have attempted regressive analysis in the Potomac Estuary.

Because regression models are not valid outside of the range of the original data, their use for flow regulation for a system of multiple-reservoirs is rather limited. Further, after analyzing various regression equations used for determining pollution control needs, Thomas[8] has suggested that this technique is more suitable for data reduction for use in the Streeter and Phelps formulation than it is for development of a predictive model.

Thomas[30] developed a queueing model employing probability theory and finite Markov chains for pollution transport in streams. The object of the model was to predict the quantity and quality of water at given control points for any pattern of flow, temperature, solar radiation, channel configuration, dam location, and pattern or type of pollution. The model includes a stochastic formulation of hydrology with lag-one serial correlation between flows; pollutants with both lag-one serial correlation and a decay mechanism. The model is limited to a single set of stream reaches. Although many of the parameters for self-purification in the oxygen budget are not included, the model represents the first attempt to incorporate two interdependent stochastic parameters, stream flow and wastewater.

Loucks[31,32] developed a mathematical model to predict the probability distribution of the minimum dissolved oxygen concentration which occurs downstream from any wastewater treatment facility. The model has utility for determination of stream standards and treatment requirements that maximize net benefits, for a given economic benefit loss function.

Wastler[33] studied interactions of tides, solar radiation, river flow, and waste loads in the Potomac Estuary with the aid of spectral analysis, including the computation of cross-spectra. The cross-spectra were used to gain quantitative information on the response of a change in DO as a function of a change in BOD. Spectral and cross-spectrum analysis was used very successfully as a statistical tool in the Potomac River and more recently in the Delaware River Estuarine Studies[34].

River Flow Simulation

The use of stream flow simulation to evaluate a given wastewater treatment policy or for design and operation of a system of dams in water resources management, makes maximum use of information available from a given hydrologic record.

A model for synthetically extending a given historical, hydrological record has been advanced largely through the efforts of Thomas and Fiering[37,48]. The model, a lag-one Markov process, may be represented by the equation

$$X_{i+1} = \mu + \beta (X_i - \mu) + t_{i+1} \sigma(1 - \rho^2)^{\frac{1}{2}} \qquad \text{- - - - - (2-16)}$$

in which

X_{i+1} = The flow in the i+1 interval, a linear function of X_i

X_i = The flow in the "i"th interval

t_{i+1} = The standardized random deviate

μ = Population mean

σ = Population standard deviation

β = Regression coefficient for the values of flows in the i+1 and "i"th interval

ρ = Correlation coefficient between flows in successive time periods.

The Markov model as given above was expanded to simulate the stream flows in an entire river basin by Fiering[37]. The model uses principal components to maintain first and second moments, serial, and spatial correlation for all stream gaging stations in the basin.

Matalas[39] has proposed a more sophisticated simulation model which maintains the third moment, and spatial and serial correlation more effectively. Other developments in flow generation have been provided by Chow[40], Beard[41], Crawford[42], and ABT Associates[43], and, more recently, on the "regional" basis by the United States Geological Survey[44].

Simulation is currently being used quite extensively in the United States in water resource planning and evaluation. The Harvard Water Resources Group[36] has designed a simulation model for the Lehigh River to aid in identification of the particular combination of flow-regulating structures, treatment plants, and other hydraulic works which most nearly achieves the objectives of the Delaware Comprehensive Plan.

Simulation was also used by the United States Corps of Engineers and lately by Davis of Resources for the Future[45] in the study of the proposed reservoir system in the Potomac River Basin. Stream flow simulation is also currently being used by the Chesapeake Field Station of the Federal Water Pollution Control Administration for evaluating water quality needs in the James, Potomac, and Patuxent River Basins.

River Basin Management

Management models are algorithms which may incorporate some of the techniques mentioned above, plus some type of decision-making mechanism. Most of the past river basin developments in water resources have been primarily devoted to water quantity, and not directly towards water quality management. In water pollution control activities there have been two general types of decision models: (1) wastewater-treatment requirement models, and (2) flow-regulation models. Included in the ensuing review of these two types of models is a case study of the Potomac Estuary in which three alternatives have been considered.

A. Flow Regulation Models

Thomas and Watermeyer[46], and more recently Young[47], have summarized the research on that aspect of flow regulation relating to the probabilistic characteristics of storage systems and dynamic decision making. Thomas describes the flow regulation problem as one of choosing:

1. the optimal operative policies;
2. the optimal level of development; and,
3. the optimal reservoir capacities.

The optimal conditions are defined in economic terms as the expected net benefits of the reservoir system.

Dorfman[48] has studied the relationships between design and operation decisions. A mathematical model for analyzing a hypothetical system involving two dams for the development of an irrigation and hydroelectric project has been proposed. Dorfman obtained an optimal design deduced from operating considerations.

Thomas and Watermeyer[46], utilizing linear programming, proposed a model for the reservoir operation problem. The model optimizes the operating policy and the levels of development and, by sampling, the reservoir capacity. It has the further advantage over the Dorfman model that the stream flow is treated as a stochastic variable. The model, limited to a single reservoir, has no mechanism for incorporating quality considerations.

Hall[49] has applied dynamic programming for allocating water for various purposes such as hydroelectric power generation, consumptive use, and water quality control. The model proposed by Hall is limited to the economic considerations involved in the design of a single reservoir. However, the application of dynamic programming for designing multiple-purpose water projects was shown.

In order to evaluate the need for, and the value of, storage for quality control according to United States Public Law 660, Worley[50] has developed a general river basin model capable of determining and adjusting flows necessary to maintain a minimum allowable dissolved oxygen concentration in a stream. The model was not an optimum-seeking model; that is, there was no mechanism incorporated that would provide for the best operation of a reservoir system.

The model does have the advantage that reservoir quality is taken into consideration. Another advantage of the Worley model is that for any given flow rate, the effect of the physical parameters of the basin is incorporated into the quality determinations. There are no economic considerations in the model.

Young[47] has developed two Monte Carlo techniques for finding the optimal annual operating policies for single reservoirs such that the economic loss as a function of draft rate is minimized. Hydrologic simulation and a forward-looking dynamic programming algorithm is used in the solution. The techniques are limited to three reservoirs. No consideration is given to the water quality in the system.

B. Treatment Requirements

Various methods for formulation of water pollution control policies with regard to treatment requirements have been developed. In recent years, considerable effort has been directed toward the problems involved in finding the minimum cost of waste treatment to meet a set of stream quality standards. Thomann and Sobel[51] have presented some of the first formulations of this problem in their studies of the Delaware Estuary.

Deininger[52] has investigated alternative means for determining waste treatment policies. Least-cost linear programming, chance-constrained, and integer-programs models were formulated to determine optimal solutions.

Sobel[53] has also proposed a linear programming solution, and a mixed integer formulation for the water quality improvement problem. The maximization of the benefit-cost ratio in water resources planning has been transformed into a linear programming problem by Sobel.

Thomann[54] has utilized the results of the steady-state segmented estuary model and a linear programming formulation to determine a least-cost water pollution control policy for the Delaware Estuary.

In order to overcome non-linear cost functions, Kerri[55] has used a dissolved oxygen cost matrix to transform the least-cost formulation into a linear programming problem. Liebman[56] has used dynamic programming for determining waste treatment requirements for problems involving non-linear cost functions.

While the least-cost solutions are of great interest in water resources planning and management, there are some inherent technical difficulties in the use of this technique:

1. Except for some industrial waste treatment facilities, there is a poor relationship between effectiveness of treatment and cost of the waste treatment facility.
2. It is difficult to estimate with any accuracy the cost of a proposed wastewater treatment plant.
3. The least-cost solutions are sensitive to physical parameters of the stream and to DO constraints.

For example, in the Delaware Estuary, Thomann[57] reported that, for given flow conditions, if the reaeration coefficient was overestimated by 100 percent the least-cost solution increased about 350 percent. The increase, although contrary to engineering judgment, was easily explained by Thomann. The allocation of treatment cost was also changed quite drastically. A significant change in treatment cost allocation was also reported by Liebman[56] in his studies of the Willamette River when the DO constraint was changed by 0.1 mg/l.

In the opinion of the author, the least-cost solutions have indicated two things:

1. the great sensitivity of the solution to the physical parameters in the stream; and
2. the ability to adequately describe and predict the water quality in a stream by the descriptive formulations is greatly exceeded by the accuracy maintained in the optimization processes.

C. Case Study. The Potomac Estuary

The water quality problems in the Potomac River Basin are unique in that the quality in the estuary is not greatly affected by upstream wastewater discharges. This independence, a result of the geological "fall-line" above Washington, D.C., simplifies the quality investigation for the estuary.

A large municipal wastewater load from the Washington, D.C., area is causing a serious quality problem in the estuary. The deterioration is not only due to low dissolved oxygen but also to high nutrient levels, resulting in large algal populations.

Three methods for alleviating water quality problems in the estuary are as follows:

1. a high degree of wastewater treatment including nutrient removal;
2. flow regulation from upstream reservoirs to provide dilution of wastewater; and,
3. diversion of the wastewater farther down the estuary.

In studying the various alternatives, Hetling[58], using the segmented estuary model, investigated all possible solutions and combinations of solutions. By ranking the alternatives, least-cost solutions were obtained to meet the various levels of water quality constraints.

Davis[59,60], using a sampling strategy consisting of systematically sampling the trade-off relationships among the various alternatives, also developed a method for cost minimization in the Potomac Estuary. In later studies, Davis used river flow simulation to evaluate the various alternatives.

The Potomac Estuary is an ideal case study in that there are three alternative solutions, two basic quality considerations, cost data available, and the quality for a given condition can be predicted by the segmented mathematical model.

CHAPTER III

FLOW RELEASE MODEL

THE PROBLEM

The problem pursued in this study is as follows: given a basin with a developed and/or proposed reservoir system, develop a method for formulating reservoir operating policies for quality control in some optimal manner. An optimal release sequence for the initial phase of this study is defined as providing the "best" quality of water for a given flow rate at a point in the system while maintaining a minimum preset dissolved oxygen level in all reaches of the basin above this point. The "best" quality of water is further defined as the minimum DO deficit for a given level of BOD. The method for determining the optimal release sequence should also incorporate:

1. Physical and biochemical parameters of the stream for a given section:
    a. Flow
    b. Temperature
    c. Velocity
    d. Depth
    e. Biological activity
2. Wastewater discharge parameters:
    a. Rate of discharge
    b. Concentration and characteristics of the pollutants in the wastewater
    c. Treatment policy

3. Regulated and unregulated stream flow parameters:
    a. Reservoir quality
    b. Change in quality with a change in flow
    c. Stochastic nature of the stream flow
4. Economic considerations
5. The necessary formulation to investigate various parameters which may alter spatial release patterns:
    a. Changes in reservoir quantity
    b. Changes in quality constraints
    c. Physical and biochemical parameters of the stream channel
6. A mechanism for intermodel linkage to other formulations such as the segmented estuary model or simulation
7. Facility of adaptation to computer programming.

The problem as presented above is an expansion of Worley's model to include optimal operation and cost. In contrast to Young's approach, the solutions sought are in physical space and not in time. The study approach is operationally oriented, that is, primary emphasis is placed on investigating parameters that affect the solution rather than on how the solution affects socio-economic considerations.

The study is limited to steady-state conditions and a deterministic flow system. That is, the final solution is for a given season and a prescribed flow range. A mechanism for overcoming the possible dependence on flow range is given in Chapter VI.

GENERAL APPROACH

Various methods for solving the proposed problem have been investigated, such as linear programming, application of influence lines, and dynamic programming. Due to the nature of the stream flow network in the basin, the use of dynamic programming to obtain an optimal solution was found to be an ideal approach. The general approach to the flow regulation problem has been divided into four phases:

1. the adaption of existing formulations to describe the appropriate water quality parameters in the river basin;
2. development of a paragon which describes the physical basin and is readily adaptable to computer programming;
3. utilization of the dynamic programming optimization technique; and,
4. overall algorithm formulation and computer programming of the model.

QUALITY FORMULATIONS

Quality considerations in the formulation have been limited to temperature, DO, and BOD, with the main parameter being DO. As illustrated in Figure 1, there are many factors which influence dissolved oxygen in a river. Control of flow directly affects advective transport of oxygen and reaeration. Temperature, advective transport of waste loads, and biological activity are indirectly affected by change in flow.

In order to make the problem more manageable initially, only the direct effects have been included in the study. However, provisions are made in the formulations to add the indirect effects at a later time.

The basic water quality algorithm which has been used in the present work is Thomas's modification[8] of the Streeter-Phelps equation. The integrated form of the equation may be written as

$$D(1) = Y * P + D(0) * P^2 \qquad ----- (3\text{-}1)$$

where

$Y = L_o (1 - e^{-K_1 t})$, oxygen sink

$P = e^{-(K_2 t/2)}$, reaeration parameter

$D(1)$ = Dissolved oxygen deficit at lower node

$D(0)$ = Dissolved oxygen deficit at upper node

The advantages of this formulation over others are:

1. the formulation can easily incorporate other than first order reactions;
2. solutions for the integrated forms exist for all ranges of reaeration and deaeration coefficients; and
3. if the oxygen deficit is kept to less than three mg/l indirect effects can be readily added or subtracted to the oxygen sink (Y) in the reach.

In solving the algorithm, four states are carried forward. These are DO, BOD, temperature, and the deaeration coefficient. The fifth state, which is flow, is used to calculate the reaeration coefficient and the time of travel.

Reaeration

As indicated in Figure 1, there are three main sources of dissolved oxygen. Reaeration is usually the most important factor in the dissolved oxygen budget. Various formulations are available for relating the reaeration coefficient to the depth, slope, velocity, and longitudinal diffusion in the stream channel. In this study, the reaeration formulations employed have been the non-isotrophic relationship developed by O'Connor[61]:

$$K_2 = \frac{(D_L\ V)^{1/2}}{H^{3/2}} \qquad \text{- - - - - (3-2)}$$

and the Churchill formulation[62]:

$$K_2 = \frac{5.026\ \ V^{0.969}}{H^{1.673}} \qquad \text{- - - - - (3-3)}$$

where D_L is the coefficient of diffusion of oxygen in water and all other terms are as previously defined.

Other formulations, such as those of Dobbins[13,14], Streeter and Phelps[1], and Krenkel[63], can easily be substituted into the system. The effects of the different formulations for the reaeration coefficient on the verification of the system are discussed in Appendix A.

Temperature

Since the reaeration and deaeration coefficients are temperature dependent it has been necessary to incorporate a mechanism for adding and subtracting various temperature sources and sinks. Various types of stream temperature models, as summarized by Zeller[64], have been investigated. To maintain simplicity, the exponential decay temperature model of Duttweiler[65] has been incorporated into the overall algorithm. The formulation is given below:

$$T_1 = Ts_1 + [Ts_0 - To]\ e^{-\varphi X/V} \qquad \text{- - - - - (3-4)}$$

where

φ = X/H

X = $C_1 + C_2 U_2$

C_1 = 1.35

C_2 = A constant ranging in value from 0.182 to 0.24

U_2 = The velocity of the wind

X = The distance downstream from the heat source

Ts_1 = The steady-state temperature at the downstream end of the stream reach

Ts_0 = The steady-state temperature at the upstream end of the reach

T_1 = The temperature at the downstream end of the reach

To = The temperature at the upstream end of the reach.

The modified version of the Duttweiler model provides the necessary formulation to incorporate heated discharges, varying reservoir temperatures and physical conditions of the stream. The steady-state temperatures are developed from historical traces.

The corrections for the effects of temperature on the deaeration and reaeration coefficients[62,66] are given below:

$$K_t = K_{20} * \theta^{(T-20)} \qquad ----- (3\text{-}5)$$

where

K_t = The coefficient at temperature T

K_{20} = The coefficient at T 20°C

θ = A temperature coefficient

In the formulation, temperature coefficients of 1.0471 and 1.0241 have been used in the deaeration and reaeration corrections, respectively, at selected standard temperature (20°C).

A third order polynomial for determining the solubility of dissolved oxygen in water at a given temperature (T) has been incorporated into the model. The polynomial coefficients have been those developed by the TVA[67], yielding

$$\text{Sat DO} = 14.652 - 0.41022T + 0.0079910T^2 - 0.000077779T^3 \qquad \text{- - - - - (3-6)}$$

where "Sat DO" represents the saturation concentration of dissolved oxygen at temperature (T).

Physical Parameters

In the above dissolved oxygen, reaeration, and temperature formulations, physical parameters of the stream such as width, W, velocity, V, and depth, D, are required for various ranges of flow, Q. Leopold and Maddox[68] have carried out extensive study of the changes in velocity, depth, and width for a change in flow rate at a given stream cross section. The characteristic relationships developed by these investigators for the mean values for these parameters are:

$$D = aQ^b \qquad \text{- - - - - (3-7)}$$

$$V = cQ^d \qquad \text{- - - - - (3-8)}$$

$$W = eQ^f \qquad \text{- - - - - (3-9)}$$

where a,c,e and b,d,f are characteristic coefficients and exponents for correlation with Q. Operational problems involving the use of these formulations are discussed in Appendix A.

Reservoir Quality

To provide for possible BOD, DO, and temperature variations with flow from unregulated and regulated stream sources, a linear relationship has been assumed and incorporated into the flow release model.

Extensive review of stream survey data for the unpolluted, unregulated reaches of the Potomac River Basin revealed that the linear assumption was a fair approximation for DO, BOD, and temperature. However, a recent study by Churchill and Nicholas[83] indicated that the linear assumption for a regulated system was an oversimplification. Therefore, in the developing of the optimal solutions as presented in Chapters V and VI, the water quality of all regulated and unregulated sources was assumed to be constant (a preset level) for all ranges of flow.

DESCRIPTIVE PARAGON

In order to formulate a general flow release model, it has been necessary to develop a descriptive paragon which can be used for data storage and retrieval, which adequately describes the branching of a physical basin and relates it to waste discharge points, impoundments, hydrologic conditions, etc., and which is easy to program on the computer. Various types of descriptive river basin systems were investigated such as the Storet System[69], the method used by Worley[50], and the numbering system of the FWPCA stream flow simulation model[70]. A simplified method similar to that of an arrow-and-line diagram[71] of a critical path network was adapted.

For a given segment of stream the following restrictions are to be maintained:

1. stream flow in segment remains constant;
2. all tributaries, waste discharges, or water intakes are indexed at the upper node of the segment;
3. the relationships among velocity, width, depth, and with flow in the segment remain constant;

4. only one wastewater discharge, tributary, or intake is allowed per node (if two or more above entities are close together, a greater number of shorter segments are established); and,
5. the numerical value of the upper node should be greater than the lower node (not absolutely necessary; however, it simplifies some of the coding and sorting procedures).

To aid in the computation procedures and yet maintain flexibility in data analysis, storage and retrieval, the stream nodes, wastewater discharges, and stream flow additions have been indexed as given in Appendix C. The ability to add or subtract any waste source, stream flow, or add more sections to the system is maintained if the numbering of nodes is in units of 2 or greater.

NODAL OPERATIONS

All mathematical operations are at the upper node of a given reach. For nodes at which there is an addition of flow due to a waste load or confluence with another tributary, a mass balance is made with respect to flow, pounds of BOD, and pounds of dissolved oxygen deficit. The deaeration coefficient is prorated according to the pounds of BOD of the respective contributions. The temperature of the combined system is prorated according to the flow values of the two components.

The mass balance of BOD and the prorating of the deaeration coefficient treats the system linearly and does not take into consideration any antagonistic or synergistic actions or reactions. The treatment of this entire system non-linearly is beyond the scope of this study.

DYNAMIC PROGRAMMING SOLUTION

The solution to the multiple-reservoir release problem is very amenable to dynamic programming technique. The complex problem can readily be decomposed, called staging, into a series of smaller problems. The technique* relies upon decision-making at each stage rather than trying to solve the entire N-stage optimization problem simultaneously.

There are two general approaches to the reservoir problem:

1. starting at mouth of the basin, proceeding upstream, and treating the regulated confluence points as diverging branches; or
2. starting at the uppermost point of the basin, proceeding downstream, and treating the regulated confluence point as converging branches.

Since BOD, DO, deaeration, and temperature are flow dependent, the problem is significantly simplified by the latter approach.

The overall schematic of the proposed reservoir system for the Potomac River Basin shown in Figure 2 typifies this converging structure. The reservoirs (triangles) are the controlling mechanisms, and the regulated confluences (squares) are the decision points or the stages. In the Potomac system, the converging branches structure results in a 13-multistage optimization problem.

A general solution to a multistage converging dynamic programming problem has been structured by Nemhauser[72]. Represented below,

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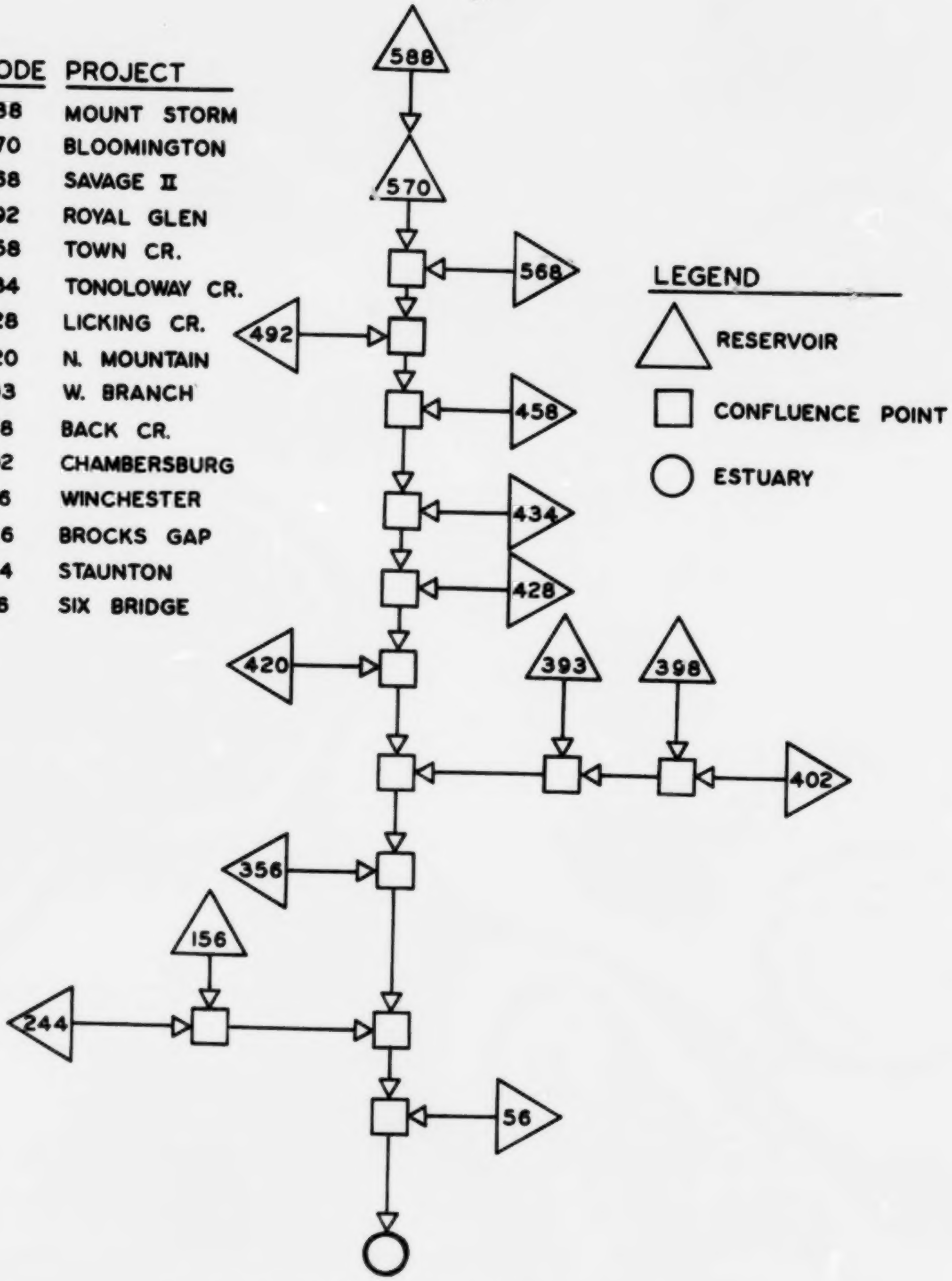
*For a complete discussion of the dynamic programming technique, see Nemhauser[72].

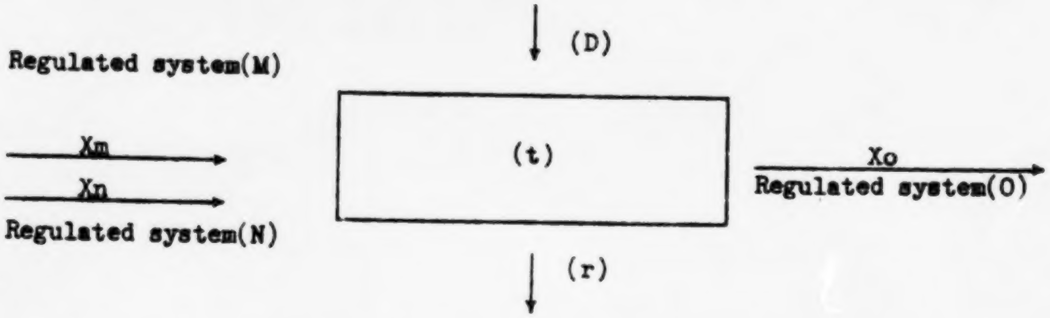
NODE	PROJECT
588	MOUNT STORM
570	BLOOMINGTON
568	SAVAGE II
492	ROYAL GLEN
458	TOWN CR.
434	TONOLOWAY CR.
428	LICKING CR.
420	N. MOUNTAIN
393	W. BRANCH
398	BACK CR.
402	CHAMBERSBURG
356	WINCHESTER
156	BROCKS GAP
244	STAUNTON
56	SIX BRIDGE


588
570
568
492
458
434
428
420
393
398
402
356
156
244
56
LEGEND
RESERVOIR
CONFLUENCE POINT
ESTUARY

A SCHEMATIC REPRESENTATION
OF
PROPOSED RESERVOIR SYSTEM - POTOMAC RIVER BASIN

Figure 2

a stage of a regulated river system is characterized by six factors:



1. An input state (Xm), flow from a regulated system (M), the dependent states being BOD, DO, deaeration, and temperature.
2. An input state (Xn), flow from a regulated system (N), the dependent states being BOD, DO, deaeration, and temperature.
3. An output state (Xo), flow from the combined regulated systems (M) and (N), the values of the dependent states being a function of a combination of (Xm) and (Xn).
4. A decision variable (D), dictates combination of (Xm) and (Xn) for a given state of (Xo).
5. A stage return (r), for a given (Xo), the best water quality measured in terms of minimum dissolved oxygen deficit (DOD for a given BOD state).
6. A stage transformation (t), couples (Xm) and (Xn) linearly, as for the dependent states described earlier in the section on nodal operations.

The flow release problem is different from the problems structured by Nemhauser in three respects:

1. each stage consists of two input states;

2. flow release optimization is required for all output states in order to provide for regulation for quality control downstream if needed; and

3. the stage return is a dual-valued function.

The latter requires a minimization decision procedure for two dependent states. In the decision process, the object is, for a given flow state, Xo, and within a given BOD grid, to determine that combination of Xn and Xm which will yield the minimum DOD. Combinations of Xm and Xn with greater DOD are deleted.

For a given stage or decision point, the range of Xo is dependent on the regulation capabilities of Xm and Xn. For example, if the regulation capability of Xm is from 100 to 300 cfs and of Xn, from 200 to 500 cfs, the range of Xo would be from 300 (200 + 100) to 800 (300 + 500) cfs. To reduce the infinite number of input and output states, reservoir releases are made in discrete increments. In the above example, if a 20 cfs increase is employed, there would be 26 states (800/20 - 300/20 + 1) of Xo. The number of feasible solutions per Xo is mainly a function of the BOD grid size.

The number of combinations of Xm and Xn which will equal a given Xo state is dependent on the value of Xo and the number of feasible solutions per states of Xm and Xn. The maximum number of combinations will be near the mean of the Xo range with a decreasing number towards the extremes of the range.

For each state of Xo, starting with the minimum and progressing to the maximum regulation capability, the optimization algorithm, which is an efficient enumeration process, consists of the following steps:

1. calculate all dependent variables for all combinations of Xm and Xn which equal the given Xo state;
2. sort and rank upward all feasible solutions according to value of BOD parameter;
3. determine BOD grid size by subtracting minimum BOD value from the maximum, comparing BOD difference to various input grids, and selecting proper BOD increment size;
4. for the given Xo and BOD values within the first increment range, select the combination of Xm and Xn which has the minimum DOD;
5. increment to the next BOD state and repeat step 4 until all feasible solutions are exhausted.

With the converging branches approach the flow regulation needs of reaches downstream from the decision point under investigation are unknown. Therefore, for a given stage, a range of feasible solutions for all states of Xo must be carried downstream.

In the initial development of the flow release model, the dual-value return function is not cumulative. The optimization process for all output states for a given stage is expressed mathematically as follows:

$$F\,(Xo(k,p)) = \text{Min}\,[DOD(k,p)\ \big|\ BOD(k,p)\ \big|\ Xo(k,p) = Xm(i) + Xn(j)] \quad \text{- - - - - (3-10)}$$

where

F (Xo(k,p)) = Optimal operation or return measured by the minimum DOD for a given BOD and flow state

Xo(k,p) = States of output Xo, k = 1,2, ... (M+N)

p = 1,2, ... P

Xm(i) = States of input Xm, i = 1,2, ... M

Xn(j) = States of input Xn, j = 1,2, ... N

as measured in

P = Maximum number of increments in BOD grid

M = Maximum number of input states for Xm

N = Maximum number of input states for Xn

BOD(k,p) = State of the first dependent variable for a given Xo state and DOD value

DOD(k,p) = State of the second dependent variable for a given Xo and BOD state.

This enumeration process makes maximum use of the natural assimilation capacity of the stream, and yet maintains the principle of optimality. If an accumulation stage return is substituted for the DOD parameter, such as a total cost parameter, the optimization procedure can easily be modified to include a minimum of cost; this is presented in Chapter VII.

OVERALL ALGORITHM AND COMPUTER PROGRAMMING

The quality and descriptive formulations adopted in the flow release model are general in nature and applicable to most river basins. The following assumptions are made in the overall formulation:

1. there is complete lateral mixing in the stream;
2. all flows are steady-state with no longitudinal diffusion;
3. the wastewater discharges are uniform in quality and quantity for a given time period;

4. all major impoundments are in the headwaters of the basin. If two or more are in series they are treated as one unit; and
5. the quality formulation as presented earlier adequately described the process in the stream.

The first three assumptions could possibly be eliminated if temporal aspects were incorporated into the model. However, other technical limitations make these refinements impractical at the present time.

In the overall computer program for the flow release model, the description paragon mathematically links the water quality formulations, multistaging process and optimization procedure to the stream network of the river basin. The paragon also selects stream flow routing patterns and sequences the multistaging process in the dynamic programming technique.

The basic computational steps of the flow release model are given below.

1. Read in and display input data.
2. Determine minimum and maximum stream flow ranges for each node in the basin. Required in the stream flow routing and multistaging process.
3. Route the unregulated stream flows to regulated sections of the basin.
4. Starting at uppermost decision point, route the stream flows and develop optimal solutions for each stage of the converging branch systems. (In Chapter V, a more detailed description of the routing, staging, and optimization process is presented along with an example problem for the upper Potomac Basin.)

5. Print out all flow routing data and optimal solutions for each stage.

A simplified flow chart* of the release model is given in Figure 3. The formulations have been programmed in FORTRAN IV, Subset E. Complete listings of the variables and computer programs are given in Appendices C, D, and E.

The input data formats are flexible to allow for various input options depending on refinements needed in the calculations (see Appendix C for data input formats and a compilation of data decks).

The output of the computer program is a series of incremental flow and dynamic programming tableaux. The incremental flow tableaux contain all pertinent information required for the optimization process, while the dynamic programming tableaux consist of the results of the process for the given decision point. The interpretation of the tableaux, development of optimal reservoir release sequence, and analysis of results are presented in Chapters V and VI.

A computer program employing the same formulations as in the flow release model was written to aid in verifying the concepts of the model. The program is also used to tabulate all input data, aid in coefficient modification, and display of specific quality profiles. A listing of the program is given in Appendix E.

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*Since flow charting capabilities via the computer are now standard subroutines at most computing centers, a detailed flow can be readily obtained and therefore was not included in the presentation.

SIMPLIFIED FLOW CHART FOR FLOW RELEASE MODEL

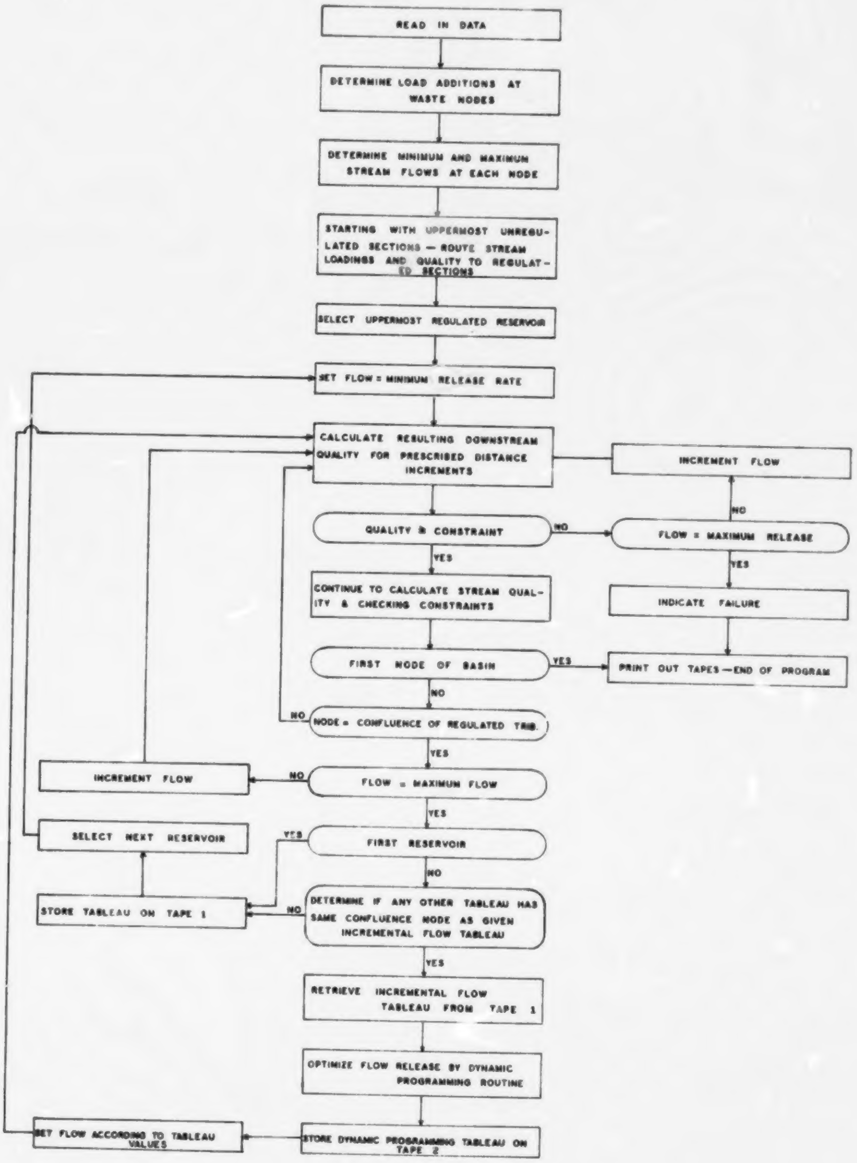

READ IN DATA
DETERMINE LOAD ADDITIONS AT WASTE NODES
DETERMINE MINIMUM AND MAXIMUM STREAM FLOWS AT EACH NODE
STARTING WITH UPPERMOST UNREGULATED SECTIONS — ROUTE STREAM LOADINGS AND QUALITY TO REGULATED SECTIONS
SELECT UPPERMOST REGULATED RESERVOIR
SET FLOW = MINIMUM RELEASE RATE
CALCULATE RESULTING DOWNSTREAM QUALITY FOR PRESCRIBED DISTANCE INCREMENTS
INCREMENT FLOW
QUALITY ≥ CONSTRAINT
NO
FLOW = MAXIMUM RELEASE
NO
YES
YES
CONTINUE TO CALCULATE STREAM QUALITY & CHECKING CONSTRAINTS
INDICATE FAILURE
FIRST NODE OF BASIN
YES
PRINT OUT TAPES—END OF PROGRAM
NO
NO
NODE = CONFLUENCE OF REGULATED TRIB.
YES
INCREMENT FLOW
NO
FLOW = MAXIMUM FLOW
YES
SELECT NEXT RESERVOIR
YES
FIRST RESERVOIR
NO
STORE TABLEAU ON TAPE 1
NO
DETERMINE IF ANY OTHER TABLEAU HAS SAME CONFLUENCE NODE AS GIVEN INCREMENTAL FLOW TABLEAU
YES
RETRIEVE INCREMENTAL FLOW TABLEAU FROM TAPE 1
OPTIMIZE FLOW RELEASE BY DYNAMIC PROGRAMMING ROUTINE
SET FLOW ACCORDING TO TABLEAU VALUES
STORE DYNAMIC PROGRAMMING TABLEAU ON TAPE 2

Figure 3

CHAPTER IV

PATUXENT AND POTOMAC RIVER BASIN SYSTEMS

Most of the emphases in the river basin models reviewed in Chapter II have been focused on the consequence of a feasible solution. Little attention has been given to physical and biochemical parameters that dictated a given solution. The lack of good field data has been the major factor limiting a comprehensive sensitivity analysis of the formulations.

To fully evaluate the flow release model and to analyze some of the controlling parameters, the formulations have been applied to two river basins in the present study, the Patuxent and the Potomac, in the Middle Atlantic Region. A brief description of the two river basin systems is presented in this chapter.

THE PATUXENT SYSTEM

The Patuxent River Basin, which has two existing reservoirs in series and a drainage area of 930 square miles, has been used for a pilot study in the testing of the quality formulations and developing methods for data analyses. There are six major sources of wastewater and two water intakes in the non-tidal portion of the basin. See Appendix C for a further description, including a schematic of the basin.

Although small in scope, the pilot study of the Patuxent River revealed the following:

1. large amounts of data are required to describe the physical and biological systems of a river basin;

2. a systematic method of data analysis and reduction is needed to implement the flow release model; and
3. a procedure for the adjustment of the various coefficients is required for model verification.

See Appendix A for a detailed description of a procedure for verification of the quality formulations.

THE POTOMAC SYSTEM

The final testing and analyses of the flow release model were done on the non-tidal portion of the Potomac River Basin, which has 15 proposed reservoirs and a drainage area of over 10,000 square miles.

The Potomac River, being located in the political center of our nation, has been studied almost continuously by various agencies since the early 1940's. The availability of data, proposed reservoir development, and current water quality problems have been decided assets in testing the formulation in the flow release model.

Source of Data

The data required for the field testing have been obtained from numerous sources, including:

1. Chesapeake Field Station, FWPCA, U. S. Department of the Interior;
2. Department of Water Resources, State of Maryland;
3. Department of Health, State of Maryland;
4. State Water Control Board, Commonwealth of Virginia;

5. Division of Sanitary Engineering, Commonwealth of Pennsylvania;
6. Division of Water Resources, State of West Virginia;
7. U. S. Geological Survey; and
8. U. S. Army Corps of Engineers.

Data also have been extracted from various technical and non-technical reports on many diverse topics concerning the Potomac Basin. Of the approximately 450 reports written concerning the Potomac, the major sources of data are references [73] through [79].

Description of Basin

The non-tidal portion of the Potomac River Basin, which contains most of the typical water quality problems, provided diverse conditions for testing the flow release model. Some of the pertinent data describing the basin is given in Table 1.

Table 1

INVENTORY OF THE POTOMAC RIVER BASIN

Entity	Quantity
Square Miles of Drainage Area	11,500
1960 Population - (Excluding Washington, D.C.)	1,000,000
Stream Miles - (Above River Mile 116.0)	2,750*
Wastewater Discharges to Streams	173
Surface Water Intakes	74

*Does not include minor tributaries

For the model development and evaluation phase of this study, only the stream reaches receiving significant wastewater discharges or those subject to flow regulation have been incorporated into the system. (See Table 2.) Included in the wastewater inventory are all discharges with a flow equal to or greater than 0.5 mgd, or a population equivalent equal to or greater than 1,000.

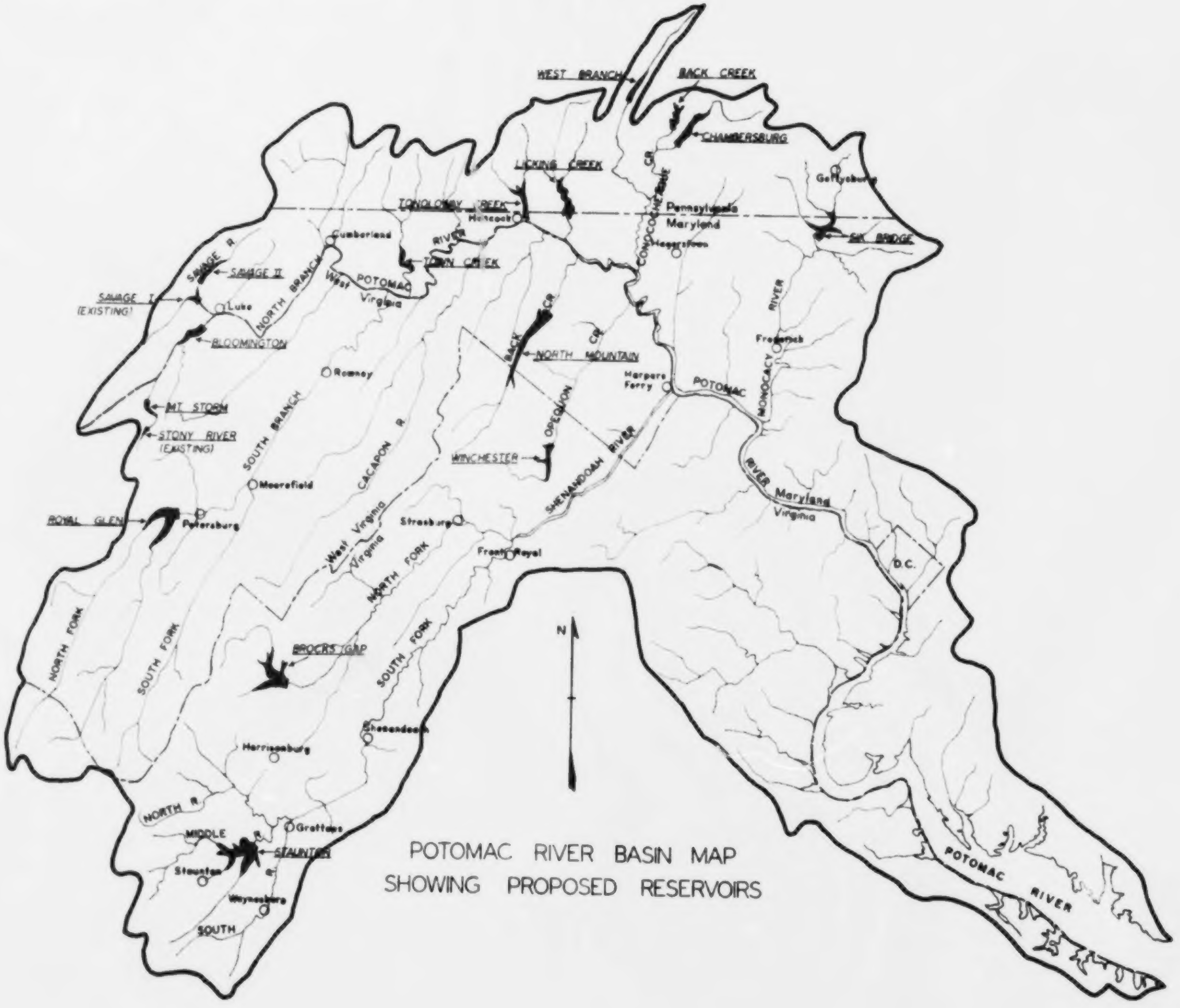
Table 2

INVENTORY OF FLOW RELEASE MODEL
FOR THE POTOMAC RIVER BASIN

Entity	Quantity
Wastewater Discharges	
Organic	64
Thermal	8
Stream Flow Addition Points	
Regulated	14
Unregulated	11
Increments	56
Surface Water Supplies	26
Stream Segments	307
Stream Miles	894
Existing Impoundments	2
Proposed Impoundments	14

The wastewater discharges included in the model represent over 90 percent of the total BOD load to the stream, and all major water supply intakes in the non-tidal portion of the Potomac Basin have been included.

Figure 4 is a general map of the Potomac River Basin, including the proposed reservoir system. In Table 3 are presented data on 14 proposed impoundments for the Potomac system. Appendix B contains detailed schematics of the individual stream reaches, showing water intakes, wastewater discharges, low level dams, gaging stations, stream segments, and reservoirs. Basin data used in the flow release model are also presented in Appendix B.



POTOMAC RIVER BASIN MAP
SHOWING PROPOSED RESERVOIRS

WEST BRANCH
BACK CREEK
CHAMBERSBURG
LICKING CREEK
TONOLOWAY CREEK
Hancock
Gettysburg
SIX BRIDGE
Pennsylvania
Maryland
Hagerstown
CONOCOCHEAGUE CR
Cumberland
POTOMAC RIVER
TOWN CREEK
West Virginia
SAVAGE R
SAVAGE II
SAVAGE I (EXISTING)
Luke
NORTH BRANCH
BLOOMINGTON
Romney
MT. STORM
STONY RIVER (EXISTING)
SOUTH BRANCH
CACAPON R
BACK CR
NORTH MOUNTAIN
OPEQUON CR
Harpers Ferry
POTOMAC
MONOCACY RIVER
Frederick
WINCHESTER
SHENANDOAH RIVER
RIVER Maryland
Virginia
D.C.
Moorefield
ROYAL GLEN
Petersburg
Strasburg
Front Royal
West Virginia
Virginia
NORTH FORK
NORTH FORK
SOUTH FORK
SOUTH FORK
BROCKS GAP
Shenandoah
Harrisonburg
N
NORTH R
MIDDLE R
Grottoes
STAUNTON
Staunton
Waynesboro
SOUTH
POTOMAC RIVER

Figure 4

Table 3

RESERVOIR DATA

Potomac River Basin

Name	Node	Total Storage (Acre-Ft)	Storage for Water Quality Control (Acre-Ft)	Total Cost ($1000)	Water Quality Control Cost ($1000)	Average Stream Flow (cfs)	Increase in Dependable Flow (cfs)
Bloomington	570	137500	92000	50865	22703	476	212
Royal Glen	492	338000	228000	30953	15744	684	484
Chambersburg	402	42800	28000	12595	9468	163	63
Staunton	244	143000	104000	24363	16485	276	163
Six Bridge	56	103000	65000	14601	6487	350	104
W. Branch	393	77500	45000	11893	5717	90	65
Brocks Gap	156	187000	120000	16641	9477	185	147
Winchester	356	77000	28300	11132	5631	77	45
Licking Creek	428	120500	82100	11528	5065	166	138
Town Creek	458	96800	57500	10009	3066	150	97
N. Mountain	420	195000	95500	16655	4655	183	137
Savage	566	50000	39000	13233	4018	73	48
Back Creek	398	46900	19700	7587	3711	72	28
Tonoloway Creek	434	88000	50000	14086	4461	118	84

CHAPTER V

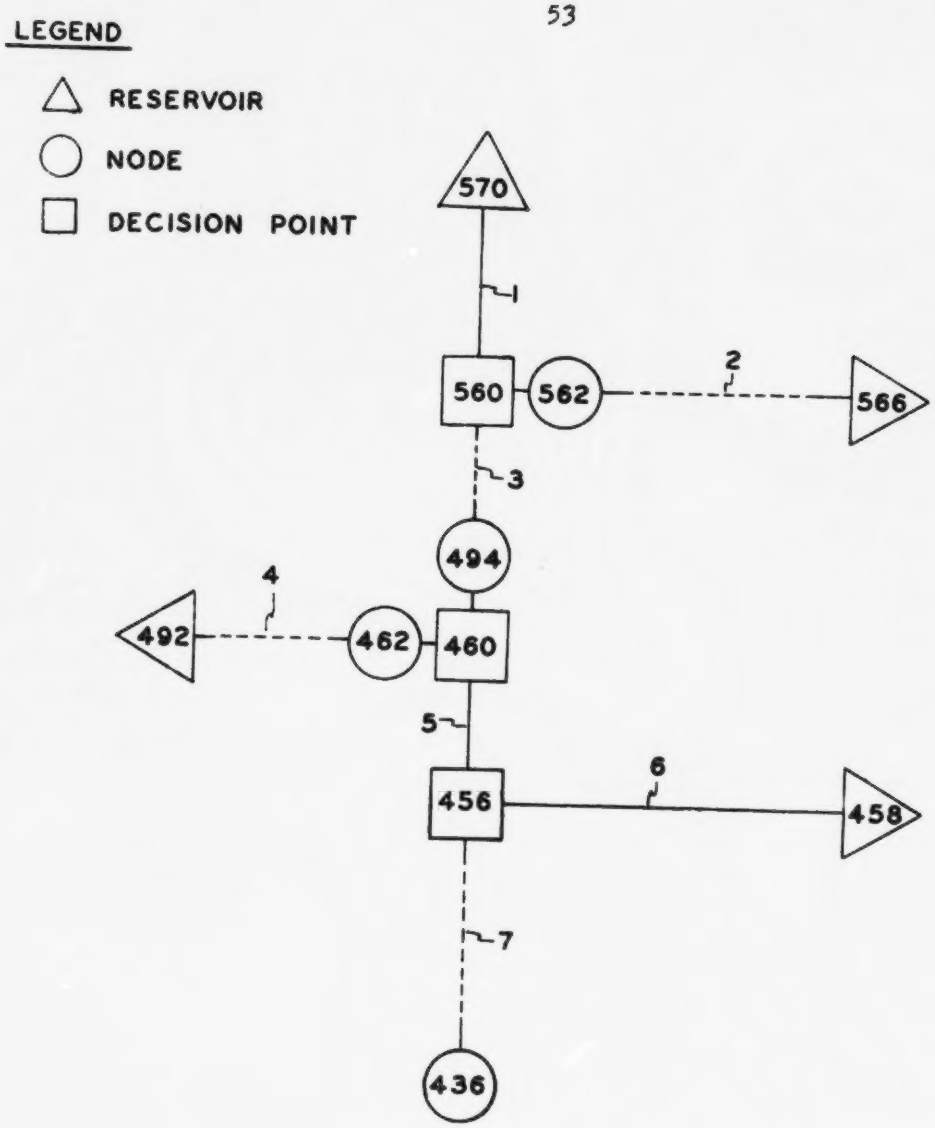
DEVELOPMENT AND INTERPRETATION OF TABLEAUX AND THE FORMATION OF RESERVOIR RELEASE PATTERNS

The most current data available have been used for testing the various quality algorithms in the computer runs of the flow release model for the Potomac River Basin. Although it has not been the main purpose of this study to obtain a completely verified model of the entire Potomac Basin, a great deal of effort, especially in the North Branch sub-basin, has been spent in data analysis so that the development, interpretation, and sensitivity analysis reported are a true indication of natural stream conditions.

The first part of this chapter is devoted to the development and interpretation of the Incremental Flow Tableaux (IFT) and the resulting Dynamic Programming Tableaux (DPT). In the latter part of this chapter, the formation of the release sequences for water quality control from multiple-reservoir systems from the tableaux is presented.

DEVELOPMENT AND INTERPRETATION OF TABLEAUX

For ease of presentation, the development and interpretation of the tableaux are limited to the upper portion of Potomac River Basin. (See Figure 5.) The entire watershed is included in the formation of general release patterns for various flow requirements at the estuary. Appendix B includes detailed schematics of the various sub-basins and a listing of the input data.


LEGEND
RESERVOIR
NODE
DECISION POINT
570
1
560
562
2
566
3
494
4
492
462
460
5
456
6
458
7
436

SCHEMATIC OF
UPPER POTOMAC RIVER BASIN
FLOW RELEASE MODEL

Figure 5

Development of Tableaux

A simplified flow chart of the entire model including the development of the tableaux within the general basin paragon is presented in Figure 3. An itemized description of the basic computational steps of the model specifically relating the formation of the various tableaux to the paragon of the upper portion of the Potomac River Basin is given below. The pertinent nodes and reaches are shown in Figure 5.

1. For reach 1 containing the Bloomington Project (node 570), set the reservoir release rate to the minimum discharge value.
2. Route flow from reservoir and resulting water quality to first decision point (node 560) incorporating into the system changes in quality or quantity resulting from any downstream waste loads, unregulated tributaries, water intakes, etc. During the routing process, the water quality is monitored at prescribed increments of distance to determine if the DO constraint is being met. If the constraint is violated, the release rate is increased by a fixed flow increment and the routing process is repeated.
3. Continue routing process from the reservoir by increasing the discharge rate by the fixed flow increment until the maximum release rate from the impoundment is obtained, thereby completing the development of the IFT for reach 1. The tableaux for reach 1 are indexed* by node 570. (See Table 4.)

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*In the model, the IFT for a given reach is indexed by the first node upstream from the decision point.

4. For reach 2 containing Savage II project (node 566), repeat the operations similar to those for the Bloomington Reservoir in steps 1, 2, and 3. The IFT for this reach is indexed by node 562. (See Table 4.)
5. Utilizing the converging branch system of dynamic programming and the enumeration process, develop for the first decision point from the IFT's of nodes 570 and 562 the optimal flow release sequences from the Bloomington and Savage II Reservoirs. The end product of the enumeration process is a DPT which contains a listing of all feasible solutions for all flow states within the minimum and maximum flow regulation capabilities of reaches 1 and 2. (See Table 8 for a DPT for node 560.)
6. Similar to the operations in step 2, in reach 3 route all feasible solutions of the above decision point to the next downstream decision point (node 460). The IFT for reach 3 is indexed by node 494. (See Table 4.)
7. For reach 4 containing the Royal Glen Project (node 492), repeat the operations similar to those for the Bloomington Reservoir in steps 1, 2, and 3. The IFT for this reach is indexed by node 462. (See Table 5.)
8. As described in step 5, develop for second decision point (node 460) all optimal release sequences from Royal Glen Project and the feasible solutions in reach 3 from IFT's of nodes 462 and 494, respectively. (See Table 9 for DPT for node 460.)

9. Similar to the operations in step 2, route in reach 5 all feasible solutions of the above decision point to the next downstream decision point (node 456). The IFT for reach 5 is indexed by node 460. (See Table 6.)
10. For reach 6 containing the Town Creek Project (node 458), repeat the operations similar to those for the Bloomington Reservoir in steps 1, 2, and 3. The IFT for this reach is indexed by node 458. (See Table 5.)
11. As described in step 5, develop for the third decision point (node 456) all optimal release sequences from the Town Creek Project and the feasible solutions in reach 5 from IFT's of nodes 458 and 460, respectively. (See Table 10 for DPT for node 456.)
12. For the final reach of the upper portion of the Potomac River Basin, the terminal IFT is developed by routing all feasible solutions from the above decision point to node 436. (See Table 7.)

In summary the following aggregation of tableaux has been computed for the nodes below:

Incremental Flow Tableaux			Dynamic Programming Tableaux	
Nodes	Reaches		Nodes	Reaches
570	1	←→	560	3
562	2			
494	3	←→	460	5
462	4			
460	5	←→	436	7
458	6			
436	7	←→	Terminal IFT	

Table 4

INCREMENTAL FLOW TABLEAU

NODE 570

Flow (cfs)	BOD (mg/1)	DO Deficit (mg/1)	Sat DO (mg/1)	Temp (°C)
31.20	2.74	0.33	8.51	22.95
51.20	2.78	0.64	8.53	22.78
71.20	2.81	0.93	8.57	22.55
91.20	2.83	1.18	8.62	22.29
111.20	2.85	1.40	8.66	22.04
131.20	2.86	1.59	8.70	21.79
151.20	2.87	1.76	8.74	21.56
171.20	2.87	1.91	8.78	21.34
191.20	2.88	2.05	8.82	21.14
211.20	2.89	2.17	8.85	20.95
231.20	2.89	2.27	8.88	20.77

NODE 562

61.80	1.84	0.35	8.56	22.65
81.80	1.87	0.45	8.61	22.33
101.80	1.89	0.54	8.67	21.99

NODE 494

243.33	4.30	0.86	8.50	23.00
263.33	4.16	0.87	8.50	23.00
283.33	4.04	0.88	8.50	23.00
303.33	3.93	0.89	8.50	23.00
323.33	3.83	0.90	8.50	23.00
343.33	3.74	0.91	8.50	23.00
363.33	3.67	0.92	8.50	23.00
383.33	3.59	0.93	8.50	23.00

Table 5

INCREMENTAL FLOW TABLEAU

NODE 462

Flow (cfs)	BOD (mg/1)	DOD (mg/1)	Sat DO (mg/1)	Temp (°C)
81.10	0.73	0.10	8.53	22.78
101.10	0.79	0.09	8.53	22.82
121.10	0.84	0.09	8.52	22.85
141.10	0.89	0.09	8.52	22.87
161.10	0.93	0.09	8.52	22.89
181.10	0.96	0.09	8.51	22.90
201.10	0.99	0.10	8.51	22.91
221.10	1.02	0.10	8.51	22.92
241.10	1.05	0.10	8.51	22.93
261.10	1.07	0.10	8.51	22.93
281.10	1.09	0.11	8.51	22.94
301.10	1.11	0.11	8.51	22.94
321.10	1.13	0.11	8.51	22.94
341.10	1.15	0.12	8.51	22.95
361.10	1.16	0.12	8.51	22.95
381.10	1.18	0.12	8.51	22.95
401.10	1.19	0.13	8.51	22.96
421.10	1.21	0.13	8.51	22.96
441.10	1.22	0.13	8.50	22.96
461.10	1.23	0.14	8.50	22.96
481.10	1.25	0.14	8.50	22.96
501.10	1.26	0.14	8.50	22.96
521.10	1.27	0.15	8.50	22.97
541.10	1.28	0.15	8.50	22.97
561.10	1.29	0.15	8.50	22.97

NODE 458

5.00	1.80	0.01	8.50	23.00
25.00	1.86	0.05	8.51	22.95
45.00	1.88	0.11	8.53	22.82
65.00	1.90	0.18	8.55	22.67
85.00	1.90	0.24	8.58	22.53
105.00	1.91	0.29	8.60	22.40

Table 6

INCREMENTAL FLOW TABLEAU

NODE 460

Flow (cfs)	BOD (mg/1)	DOD (mg/1)	Sat DO (mg/1)	Temp (°C)
324.42	3.19	0.41	8.50	22.99
344.42	3.07	0.40	8.50	22.99
364.42	2.97	0.39	8.50	22.99
384.42	2.88	0.39	8.50	22.99
404.42	2.79	0.38	8.50	22.99
424.42	2.72	0.38	8.50	22.99
444.42	2.66	0.37	8.50	22.99
464.42	2.60	0.37	8.50	22.99
484.42	2.55	0.36	8.50	22.99
504.42	2.50	0.36	8.50	22.99
524.42	2.45	0.35	8.50	22.99
544.42	2.42	0.35	8.50	22.99
564.22	2.38	0.35	8.50	22.99
584.42	2.35	0.34	8.50	22.99
604.42	2.32	0.34	8.50	22.99
624.42	2.29	0.34	8.50	22.99
644.42	2.27	0.33	8.50	22.99
664.42	2.24	0.33	8.50	22.99
684.42	2.22	0.33	8.50	22.99
704.42	2.20	0.33	8.50	22.99
724.42	2.18	0.33	8.50	22.99
744.42	2.17	0.32	8.50	22.99
764.42	2.15	0.32	8.50	22.99
784.42	2.13	0.32	8.50	22.99
804.42	2.12	0.32	8.50	22.99
824.42	2.13	0.33	8.50	22.99
844.42	2.13	0.35	8.50	22.99
864.42	2.14	0.36	8.50	22.99
884.42	2.14	0.37	8.50	22.99
904.42	2.14	0.38	8.50	22.99
924.42	2.15	0.39	8.50	22.99
944.42	2.15	0.40	8.50	22.99

Table 7

INCREMENTAL FLOW TABLEAU

NODE 436

Flow (cfs)	BOD (mg/l)	DOD (mg/l)	Sat DO (mg/l)	Temp (°C)
386.42	1.15	0.11	8.50	23.00
406.42	1.16	0.12	8.50	23.00
426.42	1.18	0.12	8.50	23.00
446.42	1.17	0.12	8.50	23.00
466.42	1.16	0.12	8.50	22.99
486.42	1.16	0.12	8.50	22.99
506.42	1.15	0.13	8.50	22.99
526.42	1.15	0.13	8.50	22.99
546.42	1.15	0.13	8.50	22.99
566.42	1.15	0.13	8.50	22.99
586.42	1.15	0.13	8.50	22.99
606.42	1.15	0.14	8.50	22.99
626.42	1.15	0.14	8.50	22.99
646.42	1.15	0.14	8.50	22.99
666.42	1.15	0.14	8.50	22.99
686.42	1.15	0.14	8.50	22.99
706.42	1.15	0.14	8.50	22.99
726.42	1.15	0.15	8.50	22.99
746.42	1.15	0.15	8.50	22.99
766.42	1.15	0.15	8.50	22.99
786.42	1.16	0.15	8.50	22.99
806.42	1.16	0.15	8.50	22.99
826.42	1.16	0.16	8.50	22.99
846.42	1.16	0.16	8.50	22.98
866.42	1.15	0.16	8.50	22.98
886.42	1.16	0.16	8.50	22.98
906.42	1.17	0.16	8.50	22.98
926.42	1.17	0.16	8.50	22.98
946.42	1.18	0.17	8.50	22.98
966.42	1.19	0.17	8.50	22.98
986.42	1.19	0.17	8.50	22.98
1006.42	1.20	0.17	8.50	22.98
1026.42	1.21	0.18	8.50	22.98
1046.42	1.21	0.18	8.50	22.98
1066.42	1.22	0.18	8.50	22.98
1086.42	1.22	0.18	8.50	22.98
1106.42	1.23	0.19	8.50	22.98

Table 8

DYNAMIC PROGRAMMING TABLEAU

NODE 560

Total Flow (cfs)	Flow at 562 (cfs)	Flow at 570 (cfs)	BOD (mg/1)	DOD (mg/1)
93.00	61.80	31.20	2.14	0.34
113.00	81.80	31.20	2.11	0.42
133.00	101.80	31.20	2.09	0.49
153.00	101.80	51.20	2.19	0.57
173.00	101.80	71.20	2.27	0.70
193.00	101.80	91.20	2.33	0.84
213.00	101.80	111.20	2.39	0.99
233.00	101.80	131.20	2.43	1.13
253.00	101.80	151.20	2.47	1.27
273.00	101.80	171.20	2.51	1.40
293.00	101.80	191.20	2.54	1.52
313.00	101.80	211.20	2.56	1.64
333.00	101.80	231.20	2.58	1.74

Table 9

DYNAMIC PROGRAMMING TABLEAU

NODE 460

Total Flow (cfs)	Flow at 462 (cfs)	Flow at 494 (cfs)	BOD (mg/1)	DOD (mg/1)
324.42	81.10	243.33	3.41	0.67
344.42	101.10	243.33	3.27	0.63
364.42	121.10	243.33	3.15	0.50
384.42	141.10	243.33	3.05	0.58
404.42	161.10	243.33	2.96	0.55
424.42	181.10	243.33	2.88	0.53
444.42	201.10	243.33	2.80	0.51
464.42	221.10	243.33	2.74	0.50
484.42	241.10	243.33	2.68	0.48
504.42	261.10	243.33	2.63	0.47
524.42	281.10	243.33	2.58	0.46
544.42	301.10	243.33	2.54	0.44
564.42	321.10	243.33	2.50	0.43
584.42	341.10	243.33	2.46	0.43
604.42	361.10	243.33	2.43	0.42
624.42	381.10	243.33	2.40	0.41
644.42	401.10	243.33	2.37	0.40
664.42	421.10	243.33	2.34	0.40
684.42	441.10	243.33	2.32	0.39
704.42	461.10	243.33	2.29	0.39
724.42	481.10	243.33	2.27	0.38
744.42	501.10	243.33	2.25	0.38
764.42	521.10	243.33	2.23	0.37
784.42	541.10	243.33	2.22	0.37
804.42	561.10	243.33	2.20	0.36
824.42	561.10	243.33	2.21	0.38
844.42	561.10	263.33	2.21	0.40
864.42	561.10	283.33	2.22	0.41
884.42	561.10	303.33	2.22	0.43
904.42	561.10	323.33	2.22	0.44
924.42	561.10	343.33	2.22	0.46
944.42	561.10	363.33	2.23	0.47

Table 10

DYNAMIC PROGRAMMING TABLEAU

NODE 456

Total Flow (cfs)	Flow at 458 (cfs)	Flow at 460 (cfs)	BOD (mg/1)	DOD (mg/1)
329.42	5.00	324.42	3.17	0.40
349.42	25.00	324.42	3.10	0.38
369.42	45.00	324.42	3.04	0.37
389.42	45.00	344.42	2.94	0.37
409.42	45.00	364.42	2.85	0.36
429.42	45.00	384.42	2.77	0.36
449.42	45.00	404.42	2.70	0.35
469.42	45.00	424.42	2.64	0.35
489.42	45.00	444.42	2.59	0.35
509.42	45.00	464.42	2.54	0.34
529.42	45.00	484.42	2.49	0.34
549.42	45.00	504.42	2.45	0.34
569.42	45.00	524.42	2.41	0.33
589.42	45.00	544.42	2.38	0.33
609.42	45.00	564.42	2.35	0.33
629.42	45.00	584.42	2.32	0.33
649.42	45.00	604.42	2.29	0.32
669.42	45.00	624.42	2.27	0.32
689.42	45.00	644.42	2.24	0.32
709.42	45.00	664.42	2.22	0.32
729.42	45.00	684.42	2.18	0.32
749.42	45.00	704.42	2.18	0.31
769.42	45.00	724.42	2.17	0.31
789.42	45.00	744.42	2.15	0.31
809.42	45.00	764.42	2.13	0.31
829.42	45.00	784.42	2.12	0.31
849.42	45.00	804.42	2.11	0.31
869.42	65.00	804.42	2.10	0.31
889.42	85.00	804.42	2.10	0.31
909.42	105.00	804.42	2.10	0.32
929.42	105.00	824.42	2.10	0.33
949.42	105.00	844.42	2.11	0.34
969.42	105.00	864.42	2.11	0.35
989.42	105.00	884.42	2.12	0.36
1009.42	105.00	904.42	2.12	0.37
1029.42	105.00	924.42	2.12	0.38
1049.42	105.00	944.42	2.12	0.39

Table 11

DYNAMIC PROGRAMMING TABLEAU
(Churchill's K_2 Formulation)

NODE 456

Total Flow (cfs)	Flow at 458 (cfs)	Flow at 460 (cfs)	BOD (mg/l)	DOD (mg/l)
349.42	5.00	344.42	3.13	0.62
369.42	25.00	344.42	3.06	0.59
389.42	45.00	344.42	3.00	0.57
409.42	65.00	344.42	2.95	0.55
429.42	65.00	364.42	2.86	0.54
449.42	65.00	384.42	2.79	0.53
469.42	65.00	404.42	2.72	0.52
489.42	65.00	424.42	2.66	0.51
509.42	65.00	444.42	2.60	0.50
529.42	65.00	464.42	2.55	0.50
549.42	65.00	484.42	2.51	0.49
569.42	65.00	504.42	2.47	0.48
589.42	65.00	524.42	2.43	0.47
609.42	65.00	544.42	2.40	0.47
629.42	65.00	564.42	2.36	0.46
649.42	65.00	584.42	2.34	0.45
669.42	45.00	624.42	2.29	0.45
689.42	45.00	644.42	2.27	0.44
709.42	45.00	664.42	2.25	0.44
729.42	45.00	684.42	2.23	0.43
749.42	45.00	704.42	2.21	0.43
769.42	45.00	724.42	2.19	0.42
789.42	45.00	744.42	2.17	0.42
809.42	45.00	764.42	2.16	0.41
829.42	45.00	784.42	2.14	0.41
849.42	45.00	804.42	2.13	0.41
869.42	45.00	824.42	2.11	0.40
889.42	65.00	824.42	2.11	0.40
909.42	85.00	824.42	2.11	0.40
929.42	105.00	824.42	2.10	0.40
949.42	105.00	844.42	2.11	0.41
969.42	105.00	864.42	2.11	0.42
989.42	105.00	884.42	2.12	0.44
1009.42	105.00	904.42	2.12	0.45
1029.42	105.00	924.42	2.12	0.46
1049.42	105.00	944.42	2.12	0.47

Table 12

FLOW RANGE DATA

Upper Potomac River Basin

Node	Minimum Flow* (cfs)	Maximum Flow** (cfs)
570***	31.20	231.20
566***	61.80	101.80
562	61.80	101.80
560	93.00	333.00
494	143.33	393.33
492***	40.00	520.00
462	81.10	561.09
460	224.42	944.42
458***	5.00	105.00
456	229.42	1049.42
436	286.42	1106.42

* minimum flow for this study computed as 7-day low flow with recurrence interval of once in ten years.

** maximum flow equals minimum flow plus regulation capacity.

*** denotes reservoir sites.

Partial listing of the tableaux for conditions typical for the month of July are given in Tables 4 through 10. A reduced form of the minimum-maximum flow range listing for the above nodes is presented in Table 12.

Incremental Flow Tableaux

As an integral part of the model output, the IFT's are used for developing the release patterns and are also very useful for establishing the effects of flow regulation on the various water quality parameters. In IFT's for nodes 570, 562, 462, and 450, the effects of increasing reservoir release rates (assuming the quality in the impoundment remains constant with flow) are clearly demonstrated. In these reaches, the water quality is primarily controlled by the conditions in the impoundment and the stream reaeration capacity.

For the reservoir at nodes 570 and 568, the BOD was assumed to be 3.0 mg/1 and DO concentration 5.0 mg/1, and 2.0 mg/1 of BOD and 8.0 mg/1 DO, respectively. With the quality remaining constant with flow, the IFT for this node clearly demonstrates how the increase flow rates lessen the recovery of initial DO deficits. Similar response is shown for the reservoir at node 568, although in this case the response is not so drastic because of the longer stream reach.

The effects of the wastewater loads in reach 3, the quality constraints, and flow augmentation can be readily seen in IFT's for nodes 494 and 460. In the downstream end of reach 3, as indexed by the IFT for node 494, the flow range is from 143 to 383 cfs. (See Table 12.) However, due to large wastewater loads in reach 3, a minimum of 243 cfs is required to meet the DO quality constraint of 4.0 mg/1. This results in a feasible range of flow from 243 to 383 cfs instead of the maximum regulatable range of 143 to 383 cfs. A similar reduction is also imposed on downstream nodes affected by the release range in reach 3.

Dynamic Programming Tableaux

As can be seen in the DPT's for nodes 560, 460, and 456 in Tables 8, 9, and 10, respectively, the tableaux contains for each flow state an optimal combination of the two contributing tributaries or reaches. The tableaux also contains the flow contributions of the IFT's indexed by the first upstream node and the numerical values of the two return variables, BOD and DOD. Not included in the partial listing are two remaining state variables, temperature and deoxygenation rate. Appendix C includes a complete display of computer output of the flow release model for the Patuxent Basin.

The indexing as described above and a listing of minimum-maximum flow ranges for each node as given in Table 12 provides a simple linkage* between the DPT's and IFT's. This linkage is necessary in developing the reservoir release sequences which is discussed in the next two sections of this chapter.

Since there are no major waste sources above the first decision point (node 560), the major factor controlling the optimization process is the water quality in the proposed reservoir sites. In the dynamic programming optimization routine for node 560, 33 feasible solutions have been investigated using a flow grid of 20 cfs. With the selection of the minimum BOD increment of 0.5 mg/1, the number of feasible solutions was reduced to thirteen. Since the BOD range was never greater than 0.5 mg/1 per flow state, only one feasible solution was retained per flow state. Hence, the optimal solution for the given flow state is that combination which yields the minimum DO deficit.

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*Linkage in this study is defined as providing a mechanism, either manual or via the computer, for data transmission between the output of a series of calculations and/or decisions and the required input for a succeeding series of calculations and/or decisions.

For the second decision point (node 460), the release pattern is from the predominantly better quality of reach 4. The 200 feasible solutions were reduced optimally to 32, corresponding to the number of flow states. Similar to node 560, there is only one solution per flow state.

The DPT of the third decision point (node 456) is made of IFT's of nodes 458 and 460, which are quite different in quality. At this node, the 192 feasible solutions were reduced to 37 optimal solutions. As presented in Table 10, there is a slight vacillation in release pattern as the flow state is increased. The vacillation is even more pronounced for this node when the Churchill reaeration is used, as can be seen in Table 11. This vacillation is due to the following factors: (1) a coarse BOD grid, (2) the water quality in the reservoir at node 458, and (3) the DOD return parameter. In Chapter VI, these and other factors will be discussed in greater detail.

FLOW RELEASE PATTERNS

From the IFT's and DPT's, it is possible to determine two types of optimal reservoir release sequences: (1) "best" water quality for a given flow requirement, or (2) minimum release rates for a given water quality requirement. Assuming that all reservoirs in the upper part of the Potomac Basin are operational, the development of a release pattern is best illustrated by an example. Using the above test runs and tableaux for July, the optimal release sequences given in Table 13 would be required to provide the best water quality (minimum DOD for a given BOD state) for a flow target of 706 cfs at node 436.

Table 13

EXAMPLE OF AN OPTIMAL RELEASE SEQUENCE

Point	Node	Total Flow (cfs)	IFT		IFT	
			Node	Flow (cfs)	Node	Flow (cfs)
Terminal	436	706	--	--	--	--
3rd Decision	456	649	458*	45	460	604
2nd Decision	460	644	462*	401	494	243
1st Decision	560	193	562*	102	570*	91

*IFT's downstream from reservoirs

The above release sequences for the decision points have been developed in reverse order from which the tableaux were formed. That is, by starting with the terminal node 436, proceeding upstream, and diverging at each decision point, the flow requirements for each contributing IFT of each stage have been determined as indicated in Table 13.

From the above Table 13, Table 12, and by subtracting the flow contributions of the unregulated drainage areas, the following reservoir operating scheme has been derived for the imposed conditions:

1. Reservoir at node 570, a release rate of 91 cfs.
2. Reservoir at node 568, a release rate of 102 cfs.
3. Reservoir at node 492, a release rate of 360 cfs.
4. Reservoir at node 458, a release rate of 45 cfs.

Since the reservoir at node 568 is drawn to its maximum capacity, the draw down of the reservoir at node 570 is necessary to meet quality constraints in reach 3.

It is also possible to develop a flow release pattern which is dictated by desired quality at a decision point. For example, at node 456 a total of 529 cfs or greater would be required to maintain a BOD level of 2.5 mg/l or less. A release pattern can be obtained to maintain the BOD objective similar to the sequence developed for a given flow rate at node 436.

WATER QUALITY CONTROL CONSIDERATIONS IN RESERVOIR DESIGN

As indicated in the previous section, the flow pattern may vary for a given decision point, depending on the total flow. While it is not feasible to construct a reservoir to meet these vacillations, the existence of a trend in release patterns is as important as are absolute release sequences.

In studies at the Chesapeake Field Station, Hetling[79] determined effects of flow regulation and waste treatment on the water quality in the Potomac Estuary. Using a DO objective of 4.0 mg/l, 91, 92, and 93 percent removal of the 5-day BOD is required for 2000, 1500, and 1000 cfs of flow, respectively. The optimal flow release sequences for the proposed reservoir system to meet the three flow targets are shown in Figure 6.

These release patterns have been developed employing the following conditions:

1. Wastewater loadings and water supply usage as given in Appendix B.

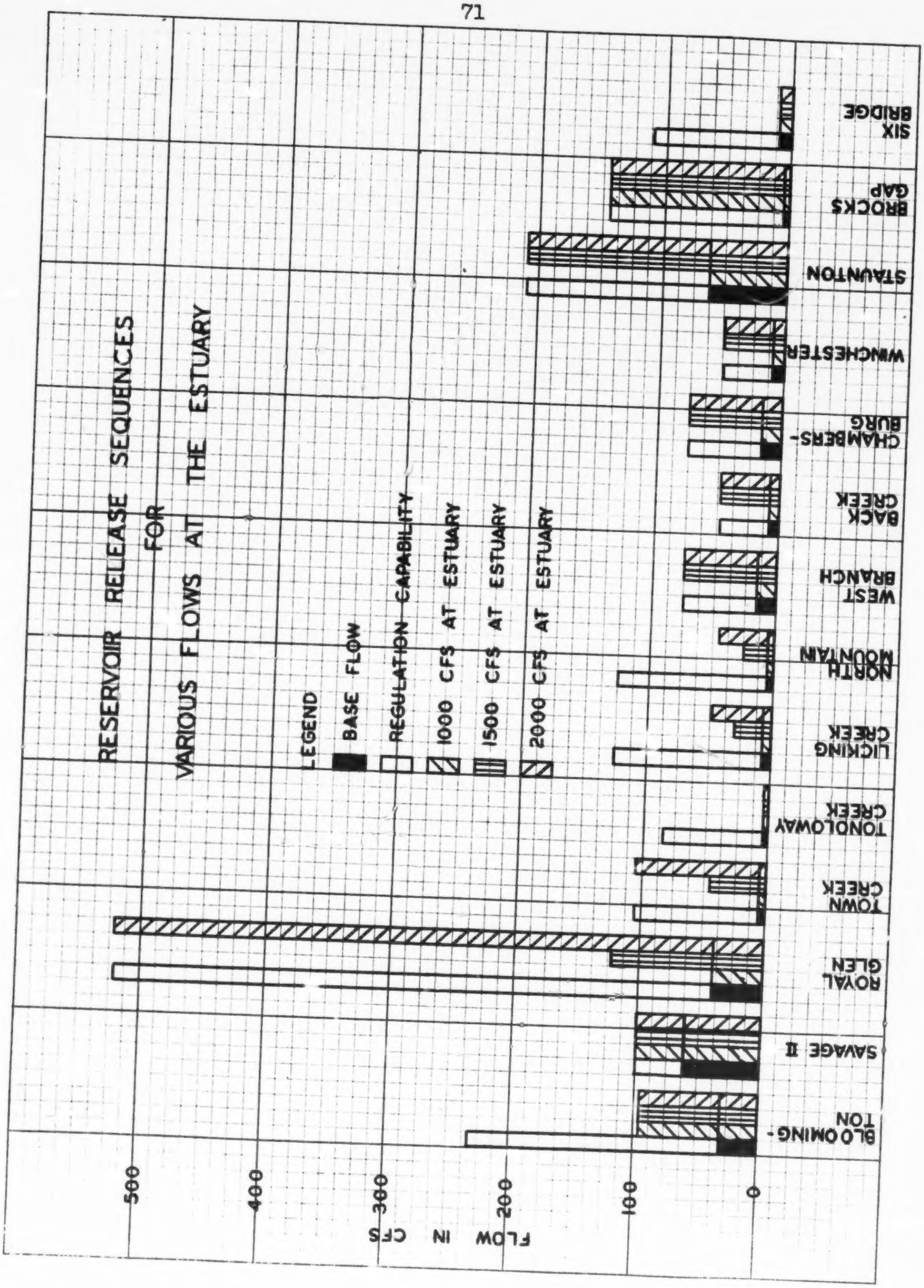

RESERVOIR RELEASE SEQUENCES
FOR
VARIOUS FLOWS AT THE ESTUARY
LEGEND
■ BASE FLOW
☐ REGULATION CAPABILITY
▨ 1000 CFS AT ESTUARY
▤ 1500 CFS AT ESTUARY
▨ 2000 CFS AT ESTUARY
FLOW IN CFS
0
100
200
300
400
500
BLOOMING-TON
SAVAGE II
ROYAL GLEN
TOWN CREEK
TONOLOWAY CREEK
LICKING CREEK
NORTH MOUNTAIN
WEST BRANCH
BACK CREEK
CHAMBERS-BURG
WINCHESTER
STAUNTON
BROCKS GAP
SIX BRIDGE

Figure 6

2. Water quality of all stream flow addition points (including reservoirs) remains constant with flow. BOD and DO are assumed to be 2.0 and 8.0 mg/1, respectively.
3. O'Connor's K_2 formulation is used to determine reaeration rate.
4. Steady-state temperature for entire river system is 23° C.
5. Base flow and regulation capacity of the reservoirs are as indicated in Figure 6.
6. DO constraint is 4.0 mg/1 in all reaches.

The above have been used also as standard test conditions for the sensitivity analysis in conjunction with 1500 cfs requirement in the estuary.

For the preceding conditions, it can be seen that the Savage II and Brocks Gap Reservoirs at nodes 104 and 568 are at their maximum release rate for all three target flows at the estuary while the Tonoloway Creek and Six Bridge Reservoirs at nodes 56 and 434 are at their base flow rates. The two reservoirs which are at their maximum rates are of primary importance in the optimal flow release pattern. The Staunton, Winchester, Chambersburg, Back Creek, and West Branch Reservoirs at nodes 244, 356, 393, 398, and 402, respectively, are utilized to their capacity at 1500 and 2000 cfs target, indicating a secondary importance in the release pattern.

In the entire Potomac River Basin affected by the proposed reservoir system, the North Branch is the only section of the Potomac that requires additional flow regulation to meet the 4.0 mg/1 DO objective. This is reflected in the constant release rates from Savage II and Bloomington Reservoirs for all targets and levels at the estuary.

CHAPTER VI

SENSITIVITY ANALYSES

In this chapter the spatial sensitivity of the reservoir release patterns are related to changes in (1) biochemical and physical, (2) design, and (3) socio-economic parameters. Comparisons of the various release sequences in response to a change in a given parameter are made to the standard test run which was described in the previous chapter and is presented in Figure 6. The biochemical and physical parameters investigated were time of travel, reaeration, minimum BOD concentrations and deaeration; the design parameters were stream temperature, BOD-DO concentrations in the proposed reservoirs, wastewater loadings, and DO concentration in the wastewater effluent; and the socio-economic parameters were water quality objectives and imposed waste loadings.

BIOCHEMICAL AND PHYSICAL PARAMETERS

The three basic biochemical and physical parameters required in the quality formulations are (1) time of travel, (2) reaeration rate, and (3) deaeration rate. Problems in determining these parameters and suggested steps in simplifying the verification of the quality formulations are given in Appendix A.

Based on verification studies in the North Branch of the Potomac River and in the Patuxent Basin, the most important parameter appears to be time of travel. An example of the importance of travel time is given in Appendix A, where a 65 percent over-estimation in time of travel resulted in a 300 percent error in calculating the assimilative capacity of the North Branch. Not only is the travel time an integral part of the water quality formulations, but also a constituent parameter in the predictive reaeration formulations and used in calculating the deaeration rate of the stream. Therefore, any analysis of the sensitivity of the flow release pattern to this parameter would also reflect changes in the temperature profile, reaeration rates, etc., and would not yield any definitive information. Also, with the use of tracers the time of travel measurement is becoming more exact and less costly.

Reaeration

Of the remaining two parameters, the reaeration rate appears to be next in importance. Even with good information on deaeration rates and times of travel, considerable engineering judgment is required in the selection and use of the reaeration formulations. In Table 15 and in Figures 13, 14, and 15, it can readily be seen that even with the same velocity and depth data, more than a threefold difference in reaeration rates can be observed depending on which formulation is used.

A test run has been made using the Churchill K_2 formulation and with all the remaining parameters being the same as in the standard test conditions. When the release pattern is compared to the standard test run (O'Connor's K_2 formulation), differences in the release rates from four reservoirs are observed. (See Figure 7.) Three of these changes are minor, 20 cfs, with the remaining being more significant, 60 cfs.

The small number of changes in the entire release pattern is primarily due to the location of the wastewater loads in the Potomac Basin. In only one section of the basin, reach 3 in the North Branch watershed, flow augmentation is required to meet the DO quality objective. The constraining section of this area (River Mile 305-310) is in waters ranging from 6 to 12 feet in depth. As can be seen in Figure 16, the two computed DO profiles are essentially the same at this critical reach, hence there is only a slight difference in the flow requirements. However, if the constraining reach had been downstream about 10 miles, the change in release pattern would have been significant.

Deaeration and Minimum BOD Concentrations

The deaeration rates of the wastewaters used in the standard test runs were either determined as outlined in Appendix A or obtained from previous water quality studies. For all stream flow addition points, a deaeration rate of 0.1 (base 10 at 20°C) was assumed.

An additional computer run was made using the standard test conditions, except that the deaeration rate of all wastewaters was set at 0.15 (base 10 at 20°C). The reservoir release sequence to maintain 1500 cfs at the estuary was very similar to the standard test run. See Figure 7 for comparison to standard test run.

The insensitivity is primarily due to the small changes in the overall stream deaeration rates. In setting all values at 0.15, some wastewater rates are increased while others are decreased, with an overall slight increase of less than 0.02 for the entire basin.

Of equal importance is the assumption of a minimum equilibrium level for BOD between the waters of the stream and the stream bed. Field studies conducted by the Chesapeake Field Station and by others indicate that there is a background BOD of 1.0 to 3.0 mg/l with a corresponding DO level of about 80 to 90 percent of saturation in long reaches of the Potomac containing no point-source pollution. With the first-order BOD decay equation used in the model, the resulting BOD

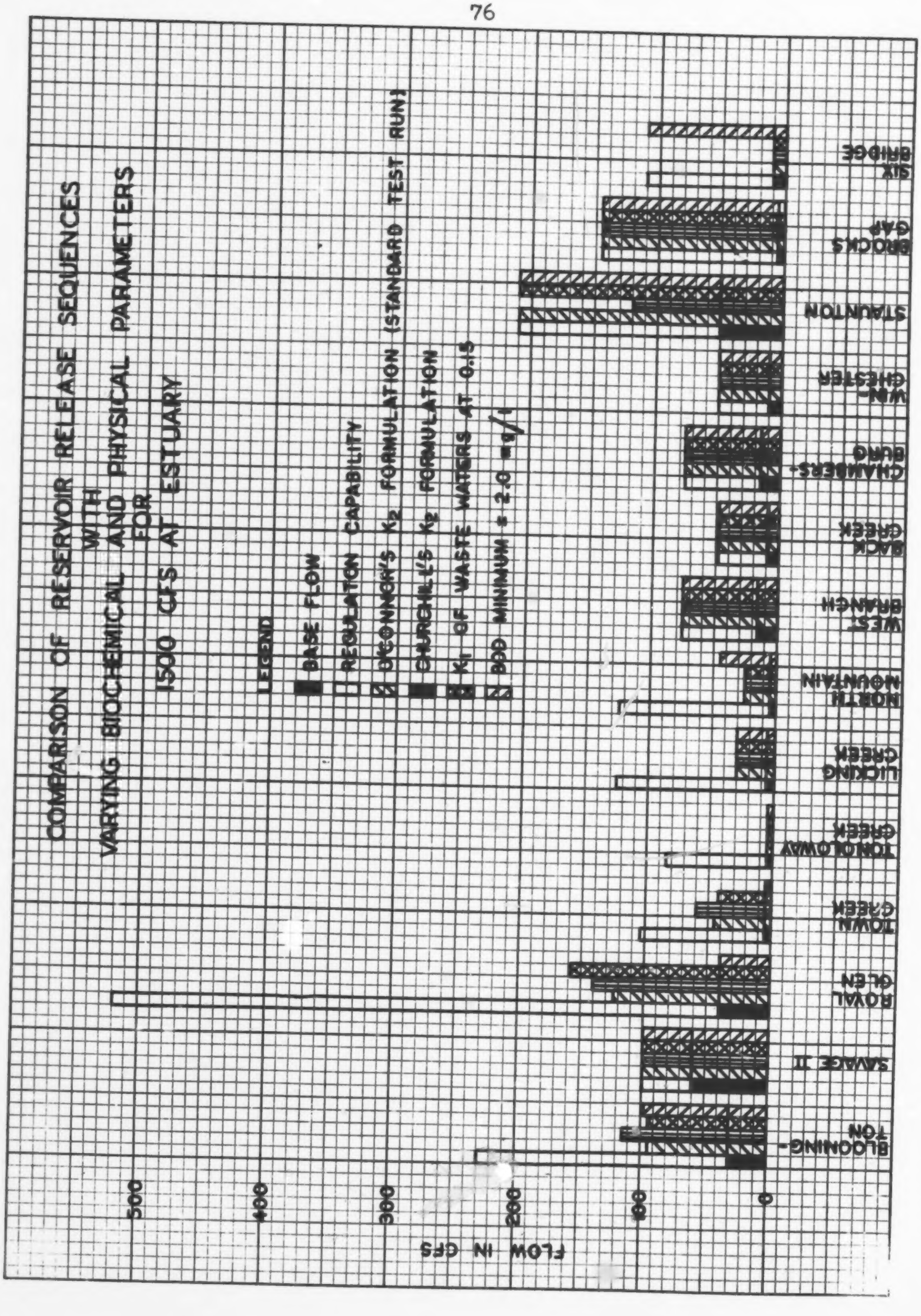

COMPARISON OF RESERVOIR RELEASE SEQUENCES
WITH
VARYING BIOCHEMICAL AND PHYSICAL PARAMETERS
FOR
1500 CFS AT ESTUARY
LEGEND
BASE FLOW
REGULATION CAPABILITY
O'CONNOR'S K_2 FORMULATION (STANDARD TEST RUN)
CHURCHILL'S K_2 FORMULATION
K_1 OF WASTE WATERS AT 0.15
DO MINIMUM = 2.0 mg/l
FLOW IN CFS
0
100
200
300
400
500
BLOOMING-TON
SAVAGE II
ROYAL GLEN
TOWN CREEK
TONOLOWAY CREEK
LICKING CREEK
NORTH MOUNTAIN
WEST BRANCH
BACK CREEK
CHAMBERS-BURG
WIN-CHESTER
STAUNTON
BROCKS GAP
SIX BRIDGE

Figure 7

concentrations approach 0.0, and the DO values are near saturation in these reaches. As can be seen in Table 7 for Node 436 (River Mile 238.0), the BOD is about 1.0 mg/l with the DO near saturation. Since there is no major point-source of pollution between Node 436 and the estuary, the BOD approaches 0.0 mg/l and the DO remains near saturation for the succeeding downstream reaches.

Under standard test conditions, a computer run was made in which the dynamic equilibrium was limited to a minimum level of 2.0 mg/l. In the run, whenever the BOD dropped below 2.0 mg/l, it was reset to 2.0 mg/l.

Major changes occurred in the release rates from Six Bridge and Royal Glen Reservoirs when compared to standard test runs. The limiting of the BOD to 2.0 mg/l causes all the reservoirs in the lower portion of the basin to draw down first. (See Figure 7.) If the existence of dynamic equilibrium level can be firmly established for various flow conditions and temperatures, the effect of this equilibrium could be significant for developing release rates for water quality control in the Potomac.

DESIGN PARAMETERS

The effects of four engineering design parameters have been investigated in this study; these are (1) temperature, (2) BOD-DO levels in the reservoir, (3) wastewater loadings, and (4) DO concentrations in the wastewater effluents.

Temperature

In the flow-release model, the temperature algorithm exponentially decays an increase or decrease in temperature to a steady-state temperature. For the standard test run a steady-state temperature of 23°C has been used, with the temperatures of the waters from the reservoirs being taken as 20°C.

The steady-state temperature was determined from a statistical analysis of the temperature data by months. The value of 23°C is an average of all the mean temperatures for the month of July for all water quality stations in the Potomac Basin.

To test the effect of temperature on the release rates, a computer run was made with the temperatures set at 28°C, with other parameters being the same as for standard test conditions. As can be seen in Figure 8, only a slight change, 20 cfs, occurred in the release sequence from four reservoirs.

With an increase in temperature, the deaeration and the reaeration rates both increase. Therefore, there is only a small net change in the maximum DO deficit which is attributed to the differences in reaction constants. The major effect of temperature is on the DO saturation concentration. This effect is most pronounced in the North Branch area which receives wastewater high in BOD and large volumes of cooling water, as can be seen in Figure 16 and where flow regulation is required to meet the DO quality constraints.

BOD-DO Concentrations in the Reservoirs

A computer run was made to investigate the effect of water quality in the reservoirs on the flow release pattern. In this run the BOD and DO were set at 3.0 and 5.0 mg/l, respectively, as compared to 2.0 and 8.0 mg/l for the standard test run.

The optimal reservoir release sequence to meet the 1500 cfs flow requirement is almost similar to that for the standard test run, except for the Royal Glen project. (See Figure 8.) The small sensitivity of the release sequence to a change in reservoir quality in the Potomac is primarily due to the location of the proposed upstream impoundments.

The distance of most impoundments from the decision points is ample to allow significant recovery of initial DO deficit imposed in the reservoirs. The extent of the recovery can be readily seen when the IFT's are examined in detail. (See Tables 4, 5, and 6.) Similar recoveries resulted for the runs when the BOD and DO were 3.0 mg/1 and 5.0 mg/1, respectively.

Wastewater Loadings

To test the sensitivity of the release sequence to changes in waste loadings, the current BOD loadings before treatment were doubled for all discharges. The release pattern developed for the doubled loading for which the minimum treatment was set at 85 percent removal of BOD is presented in Figure 8.

When compared to the standard test run, release rates from five reservoirs are changed for a doubled waste load, with Royal Glen having the greatest change of about 120 cfs. The increase in release rates from North Mountain, Licking Creek, and Town Creek follows naturally since there are no waste loads in these sub-basins.

The doubling of waste load resulted in flow requirements above the base flow in the North Fork and stem of the Shenandoah River. However, due to quality differences at the confluence point with the Potomac River, the release rates from two reservoirs in the Shenandoah sub-basin are at their maximum to meet the 1500 cfs requirements for the estuary as determined optimally using the flow release model.

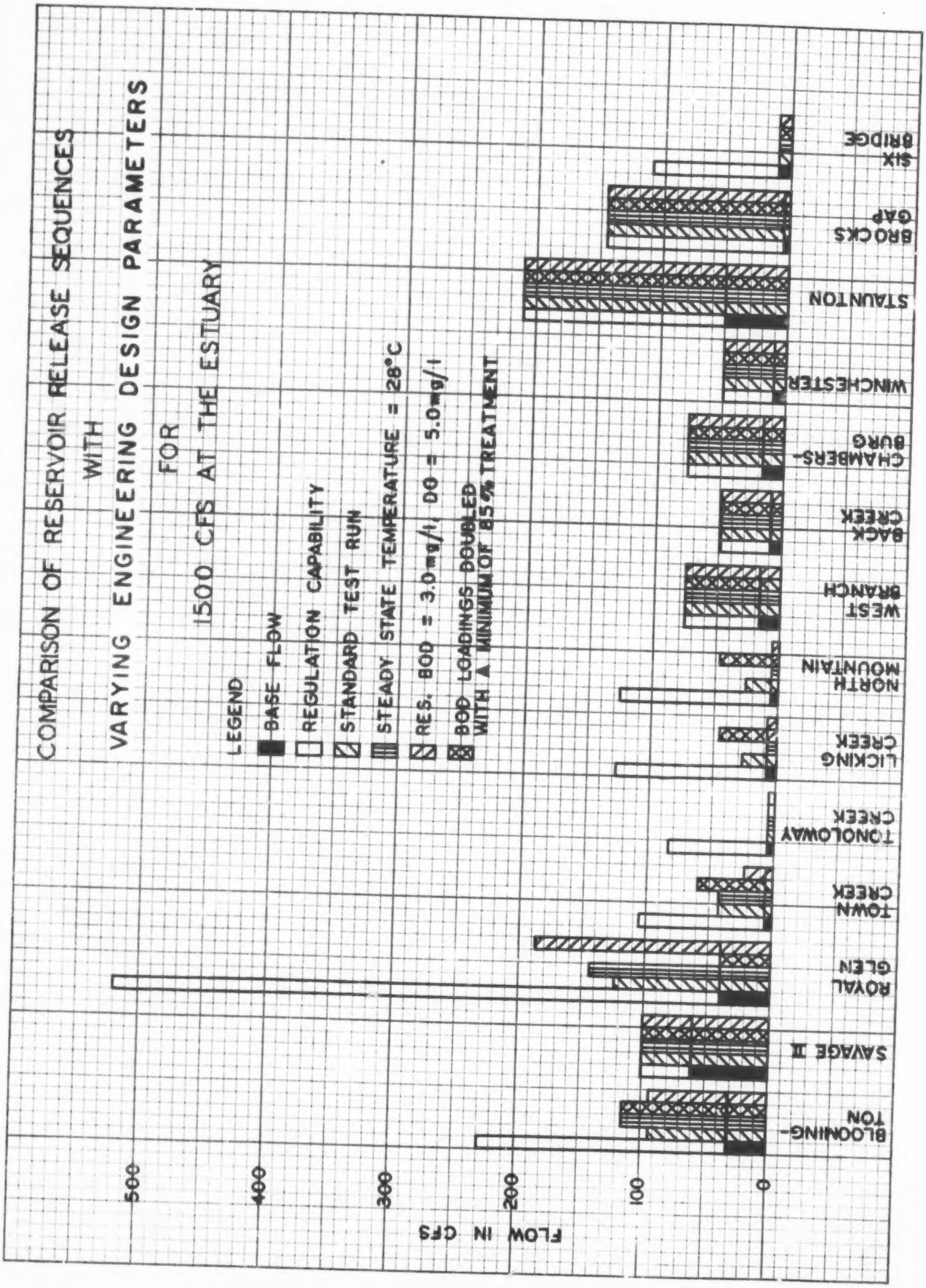

COMPARISON OF RESERVOIR RELEASE SEQUENCES
WITH
VARYING ENGINEERING DESIGN PARAMETERS
FOR
1500 CFS AT THE ESTUARY
LEGEND
BASE FLOW
REGULATION CAPABILITY
STANDARD TEST RUN
STEADY STATE TEMPERATURE = 28°C
RES. BOD = 3.0 mg/l, DO = 5.0 mg/l
BOD LOADINGS DOUBLED WITH A MINIMUM OF 85% TREATMENT
FLOW IN CFS
500
400
300
200
100
0
BLOOMING-TON
SAVAGE II
ROYAL GLEN
TOWN CREEK
TONOLOWAY CREEK
LICKING CREEK
NORTH MOUNTAIN
WEST BRANCH
BACK CREEK
CHAMBERS-BURG
WINCHESTER
STAUNTON
BROCKS GAP
SIX BRIDGE

Figure 8

DO Concentration in the Wastewater Effluents

One of the parameters often overlooked or minimized is the DO concentration in the wastewater effluents. The effects of low DO wastewater discharges are most pronounced in reaches where the ratio of wastewater to stream flow is greater than 0.5, such as the North Branch. In Figure 16, the large drops in the DO at River Mile 338 and 312 are a result of cooling water and wastewater discharges which are low in dissolved oxygen and/or have a high immediate dissolved oxygen demand.

In the model, the concentration of BOD in thermal discharges is set equal to that of intake water plus any BOD added by the industrial facility. The DO and heat content can be set at any prescribed level as input data. For the standard test runs, the DO of the large waste discharges, including cooling water, was assumed to be 0.0 mg/1.

To meet a 4.0 mg/1 DO requirement in the North Branch for the BOD loading used in the standard test, approximately 193 cfs is required at node 560. If the BOD loading is doubled with the waste volume held constant, the flow requirement is about 213 cfs. However, if the DO in the cooling water is set at 2.0 mg/1 instead of 0.0 mg/1, the flow requirement is about 173 cfs. This is a 20 cfs decrease in flow requirement even with the BOD loading being doubled. Although not shown in Figure 8, the effect of a 2.0 mg/1 change in DO in the effluent can be greater than the effect of doubling the waste loads, as illustrated above for the North Branch sub-basin, indicating the importance of this parameter in design.

SOCIO-ECONOMIC PARAMETERS

To determine the effect of selected socio-economic parameters on the release sequences, computer runs have been made for an increased water quality objective to 4.5 mg/l of DO and for imposed BOD loadings at two different reaches. The remaining parameters have been held constant as stated for the standard test runs.

Water Quality Objectives

The effect of selecting a given water quality objective can be readily observed when the sequences for the doubled BOD loadings in Figures 8 and 9 are compared. In Figure 8, the DO constraint was at 4.0 mg/l while in Figure 9, a DO constraint of 4.5 mg/l was used. The major changes in the release rates are for the Royal Glen and Bloomington Reservoirs, with minor changes for the Town Creek, Licking Creek and North Mountain projects.

The 0.5 mg/l increase in DO constraint increases the flow requirements in the North Branch by about 60 cfs. The release rates for the reservoirs or tributaries entering the main stem in the downstream portion of the Potomac, except for Six Bridge, are at their maximum rates and therefore are not affected by the increase in DO constraint.

Imposed Wastewater Loadings

To simulate the effect of an unexpected rapid growth of a community or a wastewater-producing industry in the basin, two computer runs were made with 10,000-pound BOD loadings imposed at nodes 448 and 281. The load at node 281 is on the main stem below Opequon Creek tributary. The load at node 448 is on the main stem between the tributaries of Town Creek and Tonoloway Creek. See Appendix B for further details on node locations.

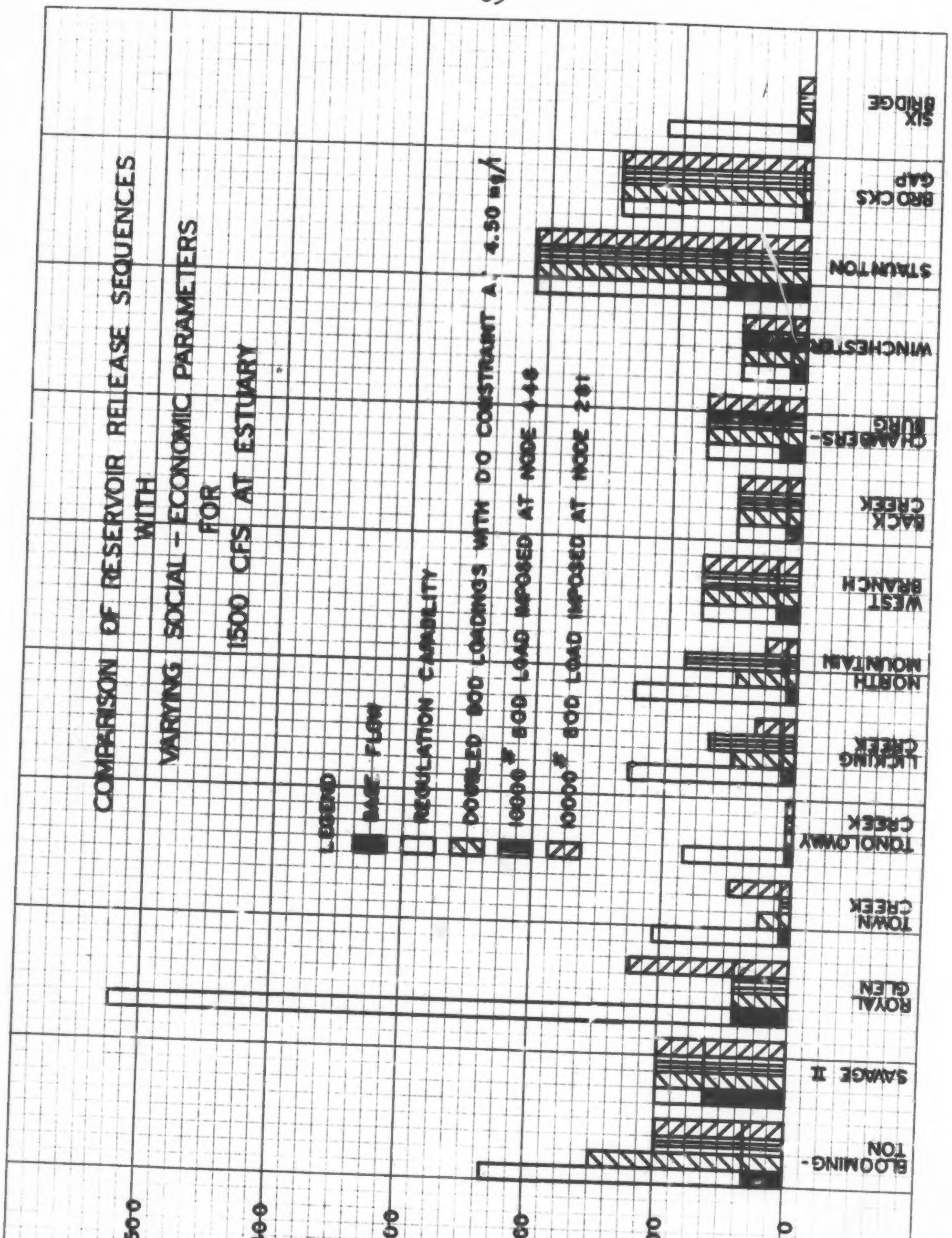

COMPARISON OF RESERVOIR RELEASE SEQUENCES
WITH
VARYING SOCIAL-ECONOMIC PARAMETERS
FOR
1500 CFS AT ESTUARY
LEGEND
BASE FLOW
REGULATION CAPABILITY
DOUBLED BOD LOADINGS WITH DO CONSTRAINT A 4.50 mg/l
10000 # BOD LOAD IMPOSED AT NODE 448
10000 # BOD LOAD IMPOSED AT NODE 281
FLOW IN CFS
0
100
200
300
400
500
BLOOMING-TON
SAVAGE II
ROYAL GLEN
TOWN CREEK
TONOLOWAY CREEK
LICKING CREEK
NORTH MOUNTAIN
WEST BRANCH
BACK CREEK
CHAMBERS-BURG
WINCHESTER
STAUNTON
BROCKS GAP
SIX BRIDGE

Figure 9

As also can be seen in Figure 9, the release sequence is sensitive to the imposed loadings at node 448, especially in the upstream portion of the basin. The release rates from four upstream reservoirs are changed with the greatest change being at the North Mountain Reservoir, about 60 cfs. However, the release sequence is not sensitive to the imposed load at node 281; in fact, the release rates are similar to those for the standard test run.

In summary, it has been demonstrated for 1500 cfs flow target at the estuary, the spatial reservoir release sequences are sensitive to changes in reaeration rates, stream temperature, wastewater loading, etc., when compared to standard test run. The greatest changes in release rates, as shown in Figures 7 to 9, were in the Bloomington, Royal Glen, Town Creek, Licking Creek, and North Mountain Reservoirs, all of which have an effect on the pollution problem originating in the North Branch. The insensitivity of the release sequences from the West Branch, Back Creek, Chambersburg, Staunton, Brocks Gap, Winchester, and Six Bridge Reservoirs is mainly due to two causes (1) relatively good water quality in these areas and (2) the seven projects and major sources of pollution are located in headwaters which allow ample time and distance for recovery of any degradation in water quality in these localized areas.

The above sensitivity analysis has been made for only one target flow at the estuary and was limited to a single parameter per test run. While other target flows and combinations of parameters may show more or less drastic changes in the release patterns, it has been well established that the release sequences are sensitive to changes of all the categories of parameters.

The grouping of the parameters as presented in Figures 7, 8, and 9 gives the engineer a great insight as to which parameter in a particular group may have the greatest effect on a given solution. The insight is even more meaningful when coupled to the ability to predict a given parameter in the future is considered. For example, of the physical and biochemical parameters, velocity and the reaeration rates for a given flow and temperature condition should remain fairly constant in the future while the deaeration rates are very dependent on the future wastewater characteristics. Fortunately, in the Potomac system the deaeration rates appear to have the least effect on the optimal flow release patterns and thereby minimizing any possible change in the release sequence due to any future changes in wastewater characteristics. The above example demonstrates how with the use of the flow release model effective planning can be realized even when all parameters cannot be accurately predicted.

CHAPTER VII

FURTHER DEVELOPMENTS OF THE FLOW RELEASE MODEL

An expanded version of the flow release model (Version II), which incorporates the cost of reservoir construction and operation, is presented in this chapter. Least-cost solutions are compared to those in Chapters V and VI, which were primarily concerned with water quality. Other possible expansions of the model, such as minimizing the deficit miles, inclusion of nutrient considerations, etc., are also proposed in this chapter.

Methods for overcoming the deterministic flow system are presented in the latter part of this chapter. Linkage to water quality, stream flow, and estuary model is also presented.

LEAST-COST SOLUTIONS

From the interpretation of DPT's in Chapter V and the sensitivity analysis in Chapter VI, it can be generally concluded that the second return variable, DOD, is not too significant in the optimisation procedure. This is especially true in the Potomac Basin or when the waste loads are not overlapping, when reservoir quality is similar, or when the DO quality constraint is high. Based on this finding, the model has been expanded to incorporate the cost of reservoir construction and operation.

The cost of reservoir storage for a given release rate was substituted for the DOD parameter as the second return variable in the optimization algorithm. To provide for non-linear cost data, the cost information is read in discrete units amenable to the flow-increment grid. This is explained in greater detail later in this chapter.

For the least-cost solution, the problem is expressed mathematically as:

$$\mathrm{Fo}(\mathrm{Xo}(k,p)) = \mathrm{Min}\ [\mathrm{Cost}(k,p) \,\big|\, \mathrm{BOD}(k,p) \,\big|\, \mathrm{Xo}(k,p) = \mathrm{Xm}(i) + \mathrm{Xn}(j)] \qquad \text{- - - - - (7-1)}$$

where

Cost(k,p) = State of the second dependent variable for a given Xo and BOD state

Fo(Xo(k,p)) = Minimum cost of flow regulation for a given flow and BOD state; other variables as defined in Chapter III.

Since the cost state is additive, an accounting mechanism is also incorporated into the model.

With Version II of the flow release model, it is possible to obtain a flow release sequence for the optimisation criteria listed in Table 14.

Table 14

OPTIMIZATION CRITERIA OF THE FLOW
RELEASE MODEL-VERSION II

Optimisation Index	First Return Variable	Second Return Variable	Remarks
I	BOD	DOD	Standard test runs
II	---	DOD	Use large BOD grid
III	BOD	COST	Least-cost solutions
IV	---	COST	Use large BOD grid
V	BOD	----	Read in all cost data as zeros

Version II also has greater flexibility in choice of reaeration prediction formulations, temperature coefficients and BOD algorithm parameters. See Appendices C, D, and E.

COMPARISON OF OPTIMIZATION PARAMETERS

Using Version II of the flow release model, a series of computer runs were made to determine the effect of various optimization parameters. As can be seen in Figure 10, release sequences are greatly affected by the choice of the optimization criterion.

In the DO deficit and BOD optimization procedure (Optimization Index 1) as discussed in Chapter V, only one solution was normally retained per flow increment even when a BOD grid as small as 0.5 mg/l was employed. The retaining of one solution per flow increment is essentially reducing the optimization to a single return variable. (Optimization Index II.)

With a smaller BOD grid, more solutions could be retained in upstream reaches of the Potomac. However, these additional feasible solutions would be eliminated at the lower decision points due to location of wastewater loadings, assumed reservoir quality, and smooth response surfaces of the BOD and DO profiles.

Similar to the above optimization parameters, the least-cost/BOD (Index III) and least-cost (Index IV) methods yield identical release sequences for the prepared reservoir system of the Potomac River Basin. The release sequences for least-BOD optimization parameter (Index V) is also given in Figure 10.

While the release sequences are very dependent on the choice of the optimization criteria, the effect on the water quality entering

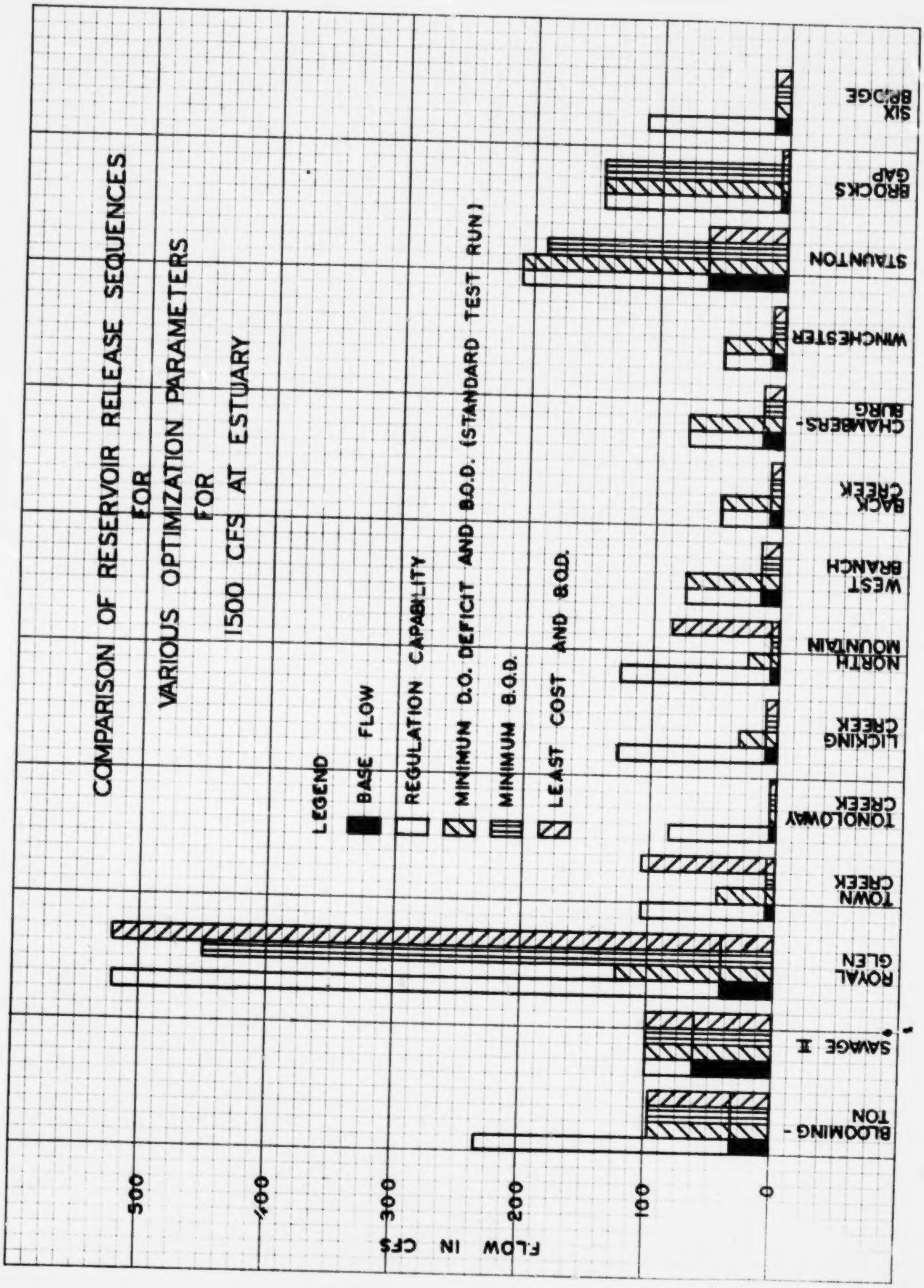

COMPARISON OF RESERVOIR RELEASE SEQUENCES
FOR
VARIOUS OPTIMIZATION PARAMETERS
FOR
1500 CFS AT ESTUARY
LEGEND
BASE FLOW
REGULATION CAPABILITY
MINIMUM D.O. DEFICIT AND B.O.D. (STANDARD TEST RUN)
MINIMUM B.O.D.
LEAST COST AND B.O.D.
FLOW IN CFS
500
400
300
200
100
0
BLOOMING-TON
SAVAGE II
ROYAL GLEN
TOWN CREEK
TONOLOWAY CREEK
LICKING CREEK
NORTH MOUNTAIN
WEST BRANCH
BACK CREEK
CHAMBERS-BURG
WINCHESTER
STAUNTON
BROCKS GAP
SIX BRIDGE

Figure 10

the estuary is minimal. Excluding the runs using a dynamic equilibrium BOD level and imposed BOD loads, the BOD and DO concentrations for 1500 cfs at the estuary vary only about 0.5 mg/l. Since the greatest difference in water quality is in the upstream tributaries of the Potomac, the release sequences for the various optimization criteria are more indicative of upstream conditions and reservoir cost for least-cost solution than they are of conditions in the main stream.

A detailed study on the cost of alternative systems for DO management in the Potomac Estuary has been made by Davis[38]. The effect of developing optimal release patterns for the non-tidal portion of basin on the various alternatives as presented by Davis is beyond the scope of this study.

OTHER POSSIBLE WATER QUALITY MEASUREMENTS

In the above flow release model, primary emphasis is given to the water quality at the decision points. While the constraints guarantee an acceptable water quality in the reach, the entire optimization procedure is based on the quality of the two contributing streams at the decision point.

With judicial use of the quality constraint and well-defined quality algorithms, one can obtain sufficient information for development of a flow release pattern; however, the solution is nonencompassing in regards to the number of stream miles at a given quality level. Three possible measurements indicative of water quality in the entire reach are as follows:

1. Number of stream miles at a prescribed water quality level, e.g., at or above a DO of 6.0 mg/l or at or above a BOD of 3.0 mg/l.
2. Number of mg/l-miles of the wastewater constituent profiles, e.g., the area under the BOD or DOD quality profiles.
3. Similar to Number 2, with the area calculation being prorated according to a predetermined scale, based on the degree of the deterioration of the water quality.

Before any of the above measurements can be applied realistically in flow regulation, it is necessary to assess wastewater treatment requirements in a similar manner. A method for financing waste treatment facilities using the constituent profile has been advanced by the State of Ohio[80].

Another water quality parameter which is receiving much attention today and which is quite indicative of stream conditions is that of nutrient level. High concentrations of nutrients, mainly phosphates and nitrates, usually result in algal blooms, which may result in further deterioration in water quality. An exponential-loss model for predicting the concentration of phosphates in flowing streams was developed as part of this study and is currently being tested at the Chesapeake Field Station. If it is possible to express the loss in phosphates mathematically, the phosphate level could be used as the second return variable, instead of the DOD parameter. See Appendix A for a description of the phosphate model.

LINKAGE TO RIVER FLOW SIMULATION MODELS

The flow release model optimizes in space, i.e., within the physical dimensions of the basin. The solutions are developed for independent time units such as months, seasons, etc. Since the solutions are independent, it is hydrologically possible that reservoir storage required for a given time unit may not be sufficient to operate optimally. The deterministic tableaux can be transformed into statistical solutions with the use of yield curves and validated with linkage to river flow simulation models.

Use of Yield Curves

Yield curves similar to that for the West Branch project can be developed for all given reservoir sites by routing historical or synthetically generated stream flows through the impoundments. (See Figure 11.)

Thirty-six years of historical data were routed through the proposed reservoir site on West Branch of the Conococheague Creek for various reservoir sizes and yield targets using the River Basin Simulation Program[81]. The probability of deficiency in months for each routing and storage capacity was determined for a prescribed uniform use rate.

The probability of failure can be introduced into the flow release sequence simply by developing such curves for each proposed site. The minimum and maximum flow regulation ranges (required input for the flow release model) can be obtained from these curves for a probability of failure. For example, for a maximum of 50,000 acre-feet of storage at West Branch site, the flow range is from a minimum of 20 cfs to a maximum of 120 cfs for 1 percent probability of failure.

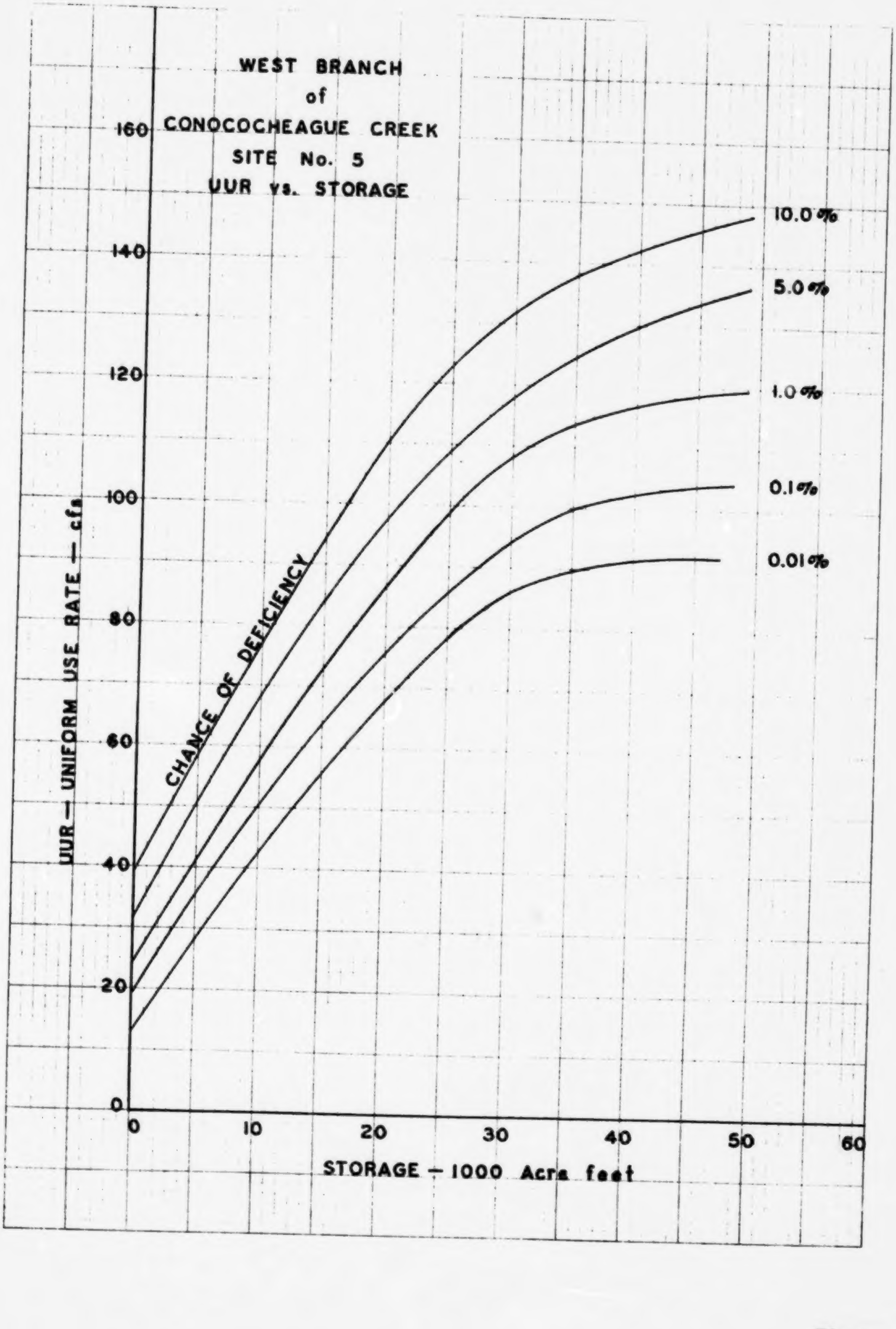

WEST BRANCH
of
CONOCOCHEAGUE CREEK
SITE No. 5
UUR vs. STORAGE
10.0 %
5.0 %
1.0 %
0.1 %
0.01 %
CHANCE OF DEFICIENCY
UUR — UNIFORM USE RATE — cfs
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60
STORAGE — 1000 Acre feet

Figure 11

Using the typical reservoir cost-storage curves as developed by the Corps of Engineers[73], it is possible to transform the Figure 11 into a uniform use rate (UUR) versus storage cost relationship for the various probabilities of deficiency. This transformation is required in the least-cost solutions.

River Flow Simulation Models

In a basin as large as the Potomac, there are great differences in rainfall patterns, ground water, terrain, etc. These differences introduce a joint probability of deficiency for each decision point.

The probability of failure in the flow release sequence developed in conjunction with the yield curves can be further evaluated by using option B of River Basin Simulation Program[81].

The operation patterns as developed from the flow release model are read in as input controls in the simulation model. The option B program attempts to maintain the prescribed releases for each reservoir for each time unit.

A more sophisticated model for river flow simulation has been developed by the Corps of Engineers and greatly expanded by Resources for the Future[82]. The simulation program has the advantage of incorporating an operating policy (release rules) that is consistent with the multiple purpose uses served by the proposed reservoirs. The release rules accomplish the objectives of maintaining reservoir pools for reaeration and flood control, as well as meeting downstream flow requirements for water supply, quality control, etc.

The feature of being able to prescribe preference release patterns for the various control points (or decision points) makes the simulation program very amenable to the solutions generated by flow release models. From the IFT's and DPT's as described in Chapter V, it is possible to determine optimal release patterns. Further, from the tableaux, it is also possible to determine for each decision point the next best level of operation. Thus, from the flow release model, one can not only determine the specific release sequence needed to operate the system optimally, but also determine the next best operational pattern in case there is insufficient storage to meet the optimal release sequence.

By using the output data of the flow release model as input data for the river flow simulation program, a linkage in determining flow requirements including the probability of failure can be realised. This linkage also can be used to statistically evaluate the significance of various physical,biochemical, design, and socio-economic parameters in regard to failure frequencies.

LINKAGE TO ESTUARY AND RIVER BASIN QUALITY - SIMULATION MODELS

In the application of the Thomann steady-state, Thomann time-dependent, or the O'Connor estuarine models, boundary conditions of flow,BOD, DO, and temperature are required. The final tableaux from flow release program contain these states, and also costs for regulation, optimally determined for each incremental flow state. By using the results of the tableaux as input for the estuary models linkage can be obtained.

A complete simulation program would be required to completely evaluate a water quality control program for an entire river basin, including its estuary. The following considerations should be incorporated in such a basin model.

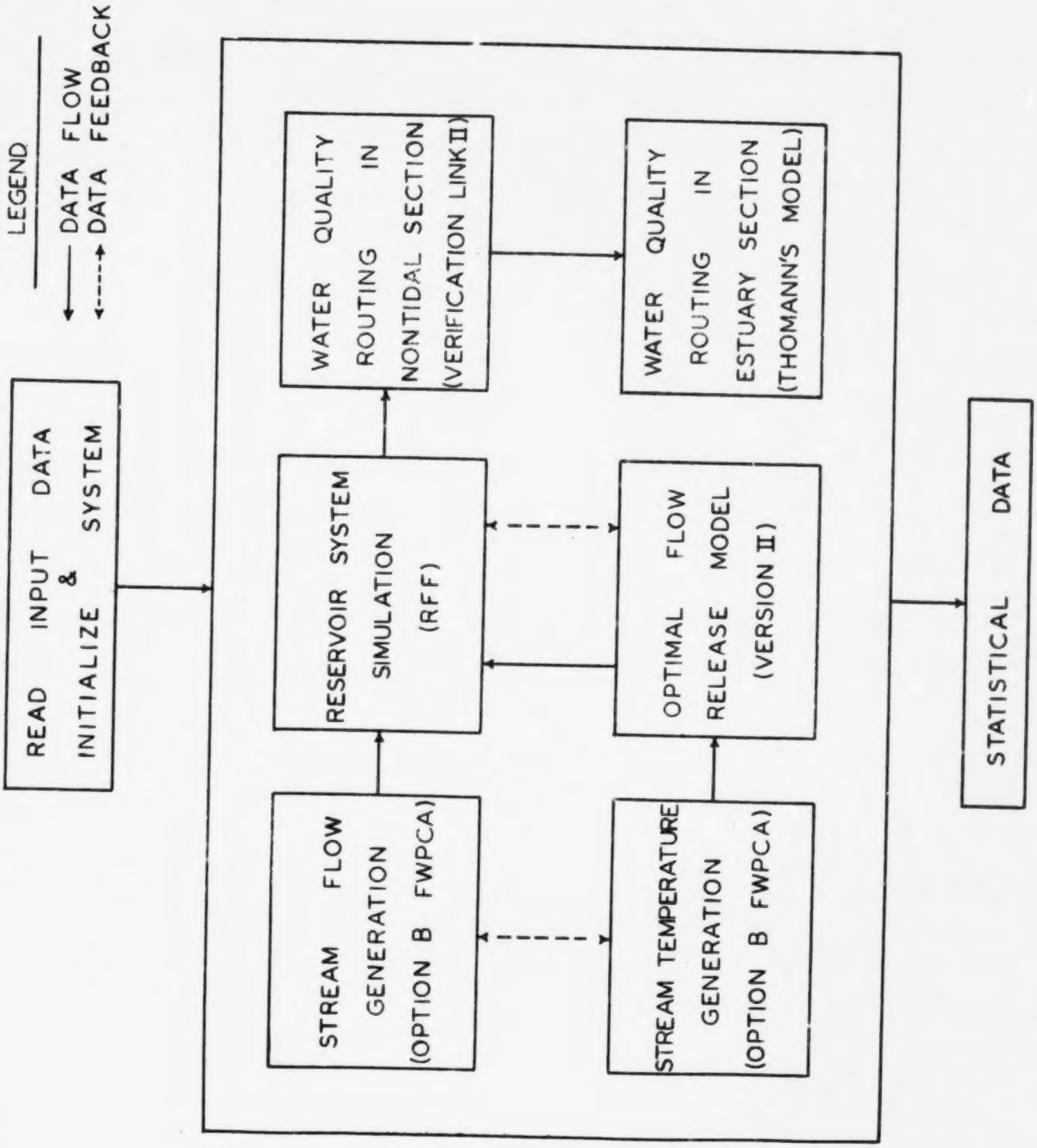
1. A mechanism for stream flow generation.
2. A mechanism for stream temperature generation.
3. A model for determining the optimal reservoir release sequences conditional on the status of the reservoirs.
4. A routing of stream flows according to optimal release sequences while maintaining given prescribed conditions in the individual reservoirs.
5. A routing of the water quality in non-tidal portion of the basin to develop the boundary conditions at the estuary.
6. A routing of the water quality in the estuary.

The simulation could be either steady-state or time-dependent.

Algorithms for many of the above steps currently exist. Since the overall program would be enormous, it probably would have to be accomplished in various links. A proposed flow chart showing the linkage of the various algorithms is presented in Figure 12.

Boundary conditions for the upper stream terminal points and imposed wastewater loads would be read in as input data. The upper boundary conditions of the estuary model would be generated from the upstream portion by the verification link.

The development of an overall basin water quality simulation model is the next logical step in evaluating any proposed water quality management program.


READ INPUT DATA & INITIALIZE SYSTEM
LEGEND
DATA FLOW
DATA FEEDBACK
STREAM FLOW GENERATION (OPTION B FWPCA)
RESERVOIR SYSTEM SIMULATION (RFF)
WATER QUALITY ROUTING IN NONTIDAL SECTION (VERIFICATION LINK II)
STREAM TEMPERATURE GENERATION (OPTION B FWPCA)
OPTIMAL FLOW RELEASE MODEL (VERSION II)
WATER QUALITY ROUTING IN ESTUARY SECTION (THOMANN'S MODEL)
STATISTICAL DATA

LINKAGE FOR RIVER BASIN WATER QUALITY SIMULATION

Figure 12

IN-STREAM IMPOUNDMENTS

In the flow release model, it has been assumed that there are no in-stream impoundments capable of flow regulation. The imposition of in-stream impoundments adds additional decision points in the flow regulation system. Further, in these impoundments the quality formulations as given in Chapter III are invalid.

One possible solution is to develop the release patterns in reaches bounded by the up-stream reservoirs and in-stream impoundments. The problem would be to (1) maintain a prescribed quality in the reach, and (2) to optimize the water quality entering the in-stream impoundments. For the lower reaches, assumptions would have to be made on the water quality leaving the in-stream impoundments. Models for predicting water quality from impoundments are currently being developed by Churchill and Nicholas[83] and Symons _et_ _al_.[84].

Another possible solution is to expand the flow release model to include the in-stream impoundment decision points. The structuring of the problem would be very similar to that of the converging branch network proposed by Nemhauser[72] and more recently by Meier and Beightler[85].

In expanding the model, it would be necessary not only to add an algorithm for optimization at the in-stream impoundments, but also to incorporate quality formulations through the impoundments. The quality formulation and coefficients will probably be specific for a given impoundment, thus it is probable that additional input data will also be required. Since the quality formulations are not fully developed and it is possible to develop the release patterns in the bounded sections, a model which incorporates in-stream impoundments would not yield any additional beneficial use at the present time.

CHAPTER VIII

DISCUSSION OF RESULTS

The adequacy and the compatability of the water quality formulations with the optimization criteria, and optimization concepts and adaptation are discussed in this chapter. Specific and general uses of the optimal release sequence are discussed in the latter part of this chapter.

QUALITY FORMULATIONS

In Chapter VI, the spatial sensitivity of the reservoir release patterns to various biochemical and physical, design, and socio-economic parameters is presented. From the release sequences presented in Chapter VI and the quality profiles shown in Figure 16, it appears (1) that the release patterns are sensitive to changes in quality parameters such as reaeration, velocity, temperature, etc. in the reaches receiving large volumes of wastewater, demonstrating the need for well verified quality formulations; and (2) that in relatively unpolluted reaches, the quality formulations, especially the BOD algorithm, used in this study were not adequate.

Two possible solutions to the inadequacy problem are (1) the inclusion of all sources and sinks of oxygen in the formulation, as reviewed in Chapter II, or (2) the assumption of a minimum dynamic equilibrium BOD level by reaches. A major factor as to which approach is taken in selecting a given formulation should be the compatability of the quality algorithms with the optimization criteria, including the indicators or measurements of overall water quality in the basin.

For the optimization criteria of BOD and DOD concentrations at the decision points, the formulation should include all sources and sinks. If a minimum dynamic equilibrium level for BOD is used, the optimization criteria should be coupled to more encompassing indicators of water quality, such as the area under the constituent profiles as suggested in Chapter VII. The ability to take either approach with only a slight modification in the algorithm as presented in the previous chapter and as discussed in the next section of this chapter makes the flow release model developed in this study a very flexible and powerful planning tool.

OPTIMIZATION CONCEPTS AND ADAPTATIONS

As described in Chapter III, the optimization procedure used in this study was an enumeration process. In conjunction with the descriptive paragon and the converging branches multistage system of dynamic programming, the enumeration process was very effective in developing the optimal flow release patterns for the proposed reservoirs in the Potomac Basin.

With the converging concept, the number of feasible solutions retained for each stage or decision point was a function of the numerical range of the first return variable (BOD), the distribution of the values of BOD within this range, and the size of the flow increment. Since a uniform flow increment was used for a given test run, the number of solutions retained per flow state was mainly dependent on the range and to a lesser extent on the distribution of BOD at each decision point.

In the optimization procedure, the range of first return variable controls the size of the BOD increment per flow state. The selection of one of five possible increment sizes depending on the range provides for maximum variation in water quality without a corresponding loss in sensitivity when the ranges of BOD are small.

During the enumeration process, only one feasible solution is retained per BOD increment. If a large BOD grid is used or if the range of BOD is very small, only one feasible solution is retained per flow increment.

For most of the test runs excluding the least-cost solutions in the Potomac Basin, the range of BOD per flow state was usually less than 0.5 mg/l. For the stages with a BOD range greater than 0.5 mg/l (the minimum increment used in the test runs), more than one solution was retained per flow state. However, in succeeding downstream decision points the range of the BOD values converged and the addition of feasible solutions were eliminated in the enumeration process.

Upon close examination of the optimal solutions for many of the stages, it was observed for a given flow state that when the release pattern yielded the minimum BOD it usually yielded the minimum DO deficit. While the two minimums do not necessarily have to occur simultaneously, this observation indicates that the second return variable (DOD) is not significant in the optimization process. This observation led to the development of the least-cost solutions as presented in Chapter VII.

The ability to control the number of feasible solutions which are carried forward in the converging concept makes the enumeration process as described above a very powerful optimization procedure. Moreover, it eliminates the need for either a complete enumeration of all feasible solutions or some other complex or time consuming optimization process such as steepest descent.

The enumeration process can be used with both non-cumulative and cumulative return variables. The need for continuous and smooth return functions is completely eliminated.

In general, the optimization technique used in this study is simple yet very flexible. Maximum use is made of water quality ranges at each decision point; and, therefore, the optimization procedure can be considered forward looking. Also, with the proper use of the input BOD grids and increments, a balance between the accuracy of water quality predictive formulations and optimization capabilities can be easily realized.

One of the disadvantages of the dynamic programming technique such as employed by Liebman[56] in comparison to linear programming is the lack of sensitivity analysis associated with the dual variables in the simplex solution. The enumeration process and resulting IFT's and DPT's developed for this study overcome this disadvantage.

For all decision points in the converging branch system, it is possible to investigate the sensitivity of various controlling parameters and to determine the effect of selecting a sub-optimal solution in any particular reach on the overall release sequence pattern. These added features of the model produce a mechanism for possible "trade-off" within the system.

The optimal reservoir release sequence as presented in Figures 7 through 10 has been developed for 1500 cfs of flow at the Potomac estuary. While the "principle of optimality"[72] is maintained for all upstream decision points or stages, the optimal solution for the estuary may not always provide the "best" solution for a particular local situation. The preference of a sub-optimal solution can occur when the quality difference at decision points is small and the reaches below it receive an insignificant amount of biodegradable wastewater.

An example of this condition for the standard test run is at the decision point for node 460. The optimal solution requires a total of about 200 cfs from the Bloomington and Savage Reservoirs, with about 120 cfs from Royal Glen impoundment. If the 60 cfs above the base flow Royal Glen were to be released from Bloomington, the minimum DO level in the North Branch would be increased by 0.5 mg/l to 4.5 mg/l. The additional release from Royal Glen contributes very little towards increasing the DO level in the South Branch, since its minimum DO level is greater than 5.0 mg/l.

The release of the additional 60 cfs from Bloomington will increase the BOD and DO deficit at node 460 to about 0.5 mg/l. However, this small increase will be greatly attenuated in reaches below node 460. This can readily be seen when the BOD and DOD concentration of the standard test runs for nodes 460 and 436 in Tables 6 and 7 are compared.

If a return variable more indicative of overall water quality as suggested in the previous section were employed, the additional 60 cfs of flow would be from Bloomington instead of Royal Glen. In lieu of using another measurement of water quality, local situations can be resolved simply by making a series of computer runs of the flow release model at different treatment levels. For decision points at which the quality difference is minimal and there are not any critical reaches below it, a trade-off between reservoirs can readily be made when the release rates are established from the IFT's and DPT's.

This type of a trade-off can also be made when economic considerations are incorporated into the optimization procedure as in the least-cost solutions. The development and use of release sequences including least-cost solutions for flow regulation and wastewater treatment are discussed in the next section.

USE OF OPTIMAL FLOW RELEASE SEQUENCES

As listed in Chapter VI, five flow release sequences can be developed, depending on the type of parameter employed in the optimization routine. The reservoir release rates, which are usually developed for monthly units of time, are also a function of temperature, treatment levels, reservoir conditions, etc. If monthly variations of the above are significant, the release rates have to be determined for each individual month.

From the individual IFT's, one can also determine the minimum flow requirements to maintain a given water quality objective. By comparing a series of tableaux at various treatment levels, the effect of wastewater treatment policies or flow regulation requirements can be readily observed. A similar approach can be taken in studying the effect of various water quality objectives.

Another valuable use of the output of the flow release model is its ability to investigate alternative methods and use trade-offs. For example, at node 494, the total cost of reservoir storage for water quality control in North Branch from Bloomington and Savage II will be about $10,000,000 for a DO objective of 4.0 mg/l. If the quality constraint is raised to 4.5 mg/l the cost of storage is increased to about $16,000,000.

The additional 60 cfs of flow needed at node 460 to meet the requirement at the estuary can be obtained from Royal Glen at a cost of about $2,600,000. If additional wastewater treatment in North Branch can result in an increase of the minimum DO level to 4.5 mg/l for less than $3,400,000 ($6,000,000 minus $2,600,000) a more economical solution can be obtained by the trade-off.

Least-cost solutions for various combinations of flow regulation and wastewater treatment levels can be readily added to the flow release model. This additional feature is not needed in the Potomac Basin as most of the waste loads are not overlapping and trade-offs can be readily made outside of the model as illustrated in the above example. If the need arises for the inclusion of the additional stages for each waste discharge, consideration should also be given to the incorporation of other measurements of water quality as return variables.

USE OF WATER QUALITY MANAGEMENT MODELS WITHIN THE FRAMEWORK OF CURRENT TECHNOLOGICAL AND INSTITUTIONAL PRACTICES

The model as developed in this study represents the first known attempt to determine an optimal flow regulation scheme for an entire river basin based on water quality considerations. One of the significant findings of the study is that most of the optimal solutions for proposed reservoir systems in the Potomac Basin are predicated on BOD and DOD concentration differentials of less than 0.5 mg/l. That is, the selection of the optimal solution for a given flow state is from a combination of release sequences which has a resulting BOD and DOD concentration differentials of less than 0.5 mg/l.

While it is possible mathematically to define an optimal solution (meaning either best quality of water for a given flow state, or minimal flow or storage requirement for a given quality objective), the reduction in storage requirement or the increase in water quality level based on these solutions for the proposed Potomac reservoir system appears to be small. The location of proposed reservoirs, low incidence of overlapping of pollution loads, and the small difference in quality of the two contributing tributaries at the decision point tend to make the quality problems in the various sub-basin areas somewhat independent of one another. Moreover, least-cost waste treatment solutions as reviewed in Chapter II would appear to have limited use in the non-tidal portion of the Potomac Basin.

While it has been clearly demonstrated that the reservoir release patterns are sensitive to various biochemical, physical, design, and socio-economic parameters, the magnitudes of the release rates appear to be dictated by quality constraints in the critical reaches, and/or by other non-quality needs such as water supply in the various sub-basins. Once the quality constraints are satisfied in the critical reaches by either flow regulation or waste treatment, the effects of increased treatment or regulation on water quality at the decision point are minimal. This effect will be further reduced when the full effect of the 1965 Water Quality Act is felt.

Intensive stream surveys have been conducted, primarily for formulation verification, in 1967 by the Chesapeake Field Station. For 30 stations sampled around-the-clock, considerable diurnal variations in BOD and DO deficit have been observed. The mean standard deviations of BOD and DO deficit were 2.06 and 2.15 mg/1, respectively. While it can be argued that mean values represent a net balance without utilizing time-dependent formulations, the BOD and DO ranges used in the optimization were greatly exceeded by the diurnal fluctuations.

With time-dependent quality formulations including all sources and sinks of oxygen, a more sensitive model could be realized. However, will the additional cost of data collection, analysis, and interpretation increase the significance of an optimal solution within the current institutional practices of the water resources planning agencies?

Based on expenditures for the Potomac data presented in Appendix B, it will cost approximately $600,000 to obtain sufficient information for a time-dependent model. Assuming about equal expenditures for an engineering evaluation of the data, the total cost could easily exceed $1,200,000.

For compatability purposes, the time-dependent quality formulations should be coupled to new "yardsticks" for overall basin quality. Until the methodology is developed and necessary data collected for assessing the monetary value of a given water quality and quantity level for a given failure rate, the present water quality control models appear to be adequate.

For an overall water resource management model, the problem can be expressed as maximizing the benefit-cost ratio. Benefits per water resource use per stream reach would be a function of quality, quantity, and failure rate. Such a concept could be easily incorporated into the framework of the flow release model as presented in the previous chapters.

Even with overall optimal planning models, will the institutional arrangements be adequate to act to implement the optimal solutions? Appropriations of funds for water resource planning by the U. S. Congress have not always been dictated by monetary considerations.

Haveman[90] in an analysis of Federal expenditures in ten southern states concluded the following:

1. "Although projects with the highest benefit-cost ratios tend to be chosen before projects with low ratios, no consistent or persistent pattern is manifested" and
2. "A somewhat stronger and more consistent motive seems to be present in both force of aid to low income and depressed areas and the drive to exploit development potential in areas of substantial opportunities to productive resources investments."

This appears to be the case in the Potomac River Basin. From the initial studies in the 1940's up to the present, the major construction activities have been in the Appalachia Region. This region is currently defined as a socially and economically "depressed" area.

While at the Chesapeake Field Station, the writer also had the opportunity to study and field test other water resources management models. In the opinion of the author, the most urgent research needs in the area of water quality management are as follows:

1. Inexpensive methods for easily obtaining large quantities of field information such as cross-sectioning, time-of-travel, chemical parameters, etc.;
2. More precise and readily adaptable water quality formulations especially for low BOD stream reaches and in low level impoundments;

3. Continued development of methods for projecting industrial water supply requirements and resulting wastewater loadings;
4. Methodology and necessary information for assessing, by individual water user, the monetary value of given water quality and quantity level for a given failure rate; and
5. Socio-economic significance of optimal river basin planning within the framework of current institutional practices.

From the operational viewpoint, the research areas delineated above are some of the next barriers to overcome in effective river basin management studies.

CHAPTER IX

SUMMARY AND CONCLUSIONS

This study has been concerned with the development and field testing of a method for determining optimal flow release sequences for water quality control from multiple reservoir systems. It has also been the intent of this study to investigate, using an actual river basin, the sensitivity of the release sequence to changes in various physical and biochemical, design, and socio-economic parameters.

The flow release problem was structured as a converging branch, multistage dynamic programming decision system. An optimal flow release model has been developed with the decision-making procedure at each stage (the confluence of two regulated streams) being an efficient enumeration process. Using both single and dual return variables, the model has five options for determining optimal release flow sequences for a given flow state at a decision point. These are (1) minimum DO deficit for a given BOD state; (2) a minimum DO deficit; (3) least-cost of reservoir storage for a given BOD state; (4) least-cost of reservoir storage; and (5) a minimum BOD.

Predictive algorithms for temperature, BOD, and DO have been incorporated in the flow release model. Ability to vary stream velocity and depth with flow has also been incorporated into the model.

A general descriptive mathematical paragon capable of representing the stream flow system of a river and its network of tributaries including its hydraulic characteristics and location of all impoundments, waste discharges, water intakes, etc., has been developed. In the flow release model, the paragon provides the required mathematical linkage for both the quality formulations and converging branch multistage decision system to the physical features of the basin.

Optimal reservoir-release sequences from the proposed impoundments in the Potomac River Basin have been developed for the control of water quality at mile point 116.0 (the start of the Potomac estuary). In developing the various optimal release sequences, a minimum preset dissolved oxygen level had to be met in all regulated systems.

The sensitivity of the release sequences developed by the flow release model to various physical and biochemical, design, and socioeconomic parameters has been investigated for the proposed reservoir system in the Potomac River Basin. Comparisons have been made to a standard test run for a flow target of 1500 cfs at the Potomac estuary. The conclusions of the sensitivity analysis and comparisons are:

1. Verification of the predictive quality formulations is essential. This requires well-established time of travel coefficients, which appear to be the most sensitive of the physical and biochemical parameters investigated. A method including a specially designed mathematical model has been developed to aid in verifying the predictive quality formulations.
2. Of the remaining physical and biochemical parameters, the reaeration coefficient was the most difficult to define and appears also to have a great effect on the release patterns.

3. Changing the quality of the water in the reservoir from 8.0 to 5.0 mg/l and 2.0 mg/l to 3.0 mg/l for DO and BOD, respectively, had only a small effect on the release pattern.
4. The release rates and spatial sequence can be affected by changes in waste loadings, stream temperatures, water quality objectives, DO concentrations in waste effluents, etc.
5. The location of wastewater discharges, impoundments, etc., and the orientation and geomorphology of the river basin play very important roles in determining release sequences. Therefore, no general conclusion can be made as to which parameter has the greatest effect unless specific conditions are stipulated.
6. The choice of the optimization criterion has a great effect on the release sequence for a given flow rate at the estuary; however, the resulting release pattern has only a minimal effect on water quality entering the estuary.
7. When dual return variables (DO deficit and BOD) were used in the optimization routine, the second return variable, DOD, was significant only for some of the upstream decision points, thus indicating a need for only one return state indicative of water quality.
8. The predictive algorithms used in the model for BOD and DO for relatively unpolluted reaches appear to be inadequate. The imposition of a dynamic-equilibrium for BOD overcomes some of the shortcomings; however, the effects of the imposition on the release sequence are significant.
9. Even with better predictive formulations, the use of concentrations, BOD and DOD, as return variables at the decision

points are not encompassing indicators of water quality conditions in the contributing reaches.

10. A need exists for a new indicator of water quality, such as the area under the constituent profile of a pollutant. The employment of this indicator for the first return variable, with cost of reservoir storage being the second return variable, would provide for a more meaningful approach in forming optimal release patterns for water quality control.
11. One of the most difficult aspects of implementing the flow release model is the obtaining of adequate, systematically collected field data. There is a definite need for better, faster, and less costly methods for collecting and analyzing field data.

A method for overcoming the deterministic nature of release rates from reservoirs has been suggested. Included in the method are the use of yield curves and linkage to river flow simulation models.

In summary, the optimal flow release model with the efficient enumeration process which was designed to make maximum use of the ranges of the return variables and to provide the compatability between the quality formulations and the optimization criteria has utility for:

1. developing an optimal flow release sequence from multiple-reservoir sites to maintain a given water quality objective, flow requirements, or for the least-cost of reservoir storage;
2. determining flow regulation needs to meet a given water quality objective for a particular stream reach in the basin;
3. investigating the sensitivity of the release sequence to various parameters;

4. demonstrating the effects of flow regulation on water quality;
5. providing a mechanism for "trade-off" between flow regulation cost and wastewater treatment costs; and
6. locating sites for possible industrial plants which would allow maximum flexibility with minimum effects on flow requirements.

A river basin model for simulating water quality is proposed in the latter part of the study. The simulation model, a logical next step, would include linkage to synthetic hydrology, river flow routing, optimal flow release, non-tidal quality routing, and estuarine models.

The model developed in this study has been used to determine optimal reservoir release sequences for water quality control under various conditions in the Potomac River Basin. The small ranges of BOD and DO deficit concentration differentials for a given flow state in the optimization procedure has been one of the most significant findings of the application phase of the study. This finding indicates that the solutions of water quality problems in most of the sub-basin are independent of one another, thus optimal reservoir release sequences based on quality control or even least-cost wastewater treatment solutions have limited significance unless a new measure of overall basin quality is utilized.

Future developments in modeling should not only include better quality formulation and measure of water quality, but also include better methods for quantizing the monetary value of water per stream reach per use based on quality, quantity, and failure rate. To avoid unnecessary expenditures and redundancies, there also exists a need for a balance in technical competency, data collection, benefit analysis, and project evaluation.

APPENDIX A

SOME COMMENTS ON MODEL VERIFICATION

In the dissolved oxygen and BOD formulations, the three most difficult and costly parameters to evaluate are the deaeration coefficient, reaeration coefficient, and time-of-travel. Some of the problems which have been encountered in the study, possible solutions and a delineation of areas in which more field data and research are needed to fully cope with the problems are presented in this appendix. A proposed model for predicting phosphates in flowing streams is also presented.

A fully detailed analysis of each of the problems is beyond the scope of this study; however, the author is of the opinion that the particular problems presented in this appendix are basic in model verification.

REAERATION COEFFICIENT

The three methods currently being used for determining reaeration rates in a given stream reach are as follows:

1. calculated from observed data;
2. prediction formulations, either empirical or theoretical; and
3. gaseous tracer technique.

Each of the methods has merit, depending on the situation, available resources, and projected use. For the flow release model, a method was required which could be used to determine the reaeration rate for all sections of the basin for various ranges of stream flow.

Calculated from Observed Reaeration Rates

In establishing the reaeration rates from observed field data, stream surveys are required for a minimum of two different stream flows with the deaeration rates and time-of-travel well established. One of the major disadvantages of this method is the great dependence of the reaeration calculation on the accuracy of the measured deaeration rate and time-of-travel, and the ability to identify and quantize other sources and sinks of oxygen. An error in determining the time-of-travel is reflected in the deaeration rate and must be compensated for in establishing the reaeration coefficient.

For example, in 1954 while studying the North Branch of Potomac River, Fuhrman[78] over-estimated the travel time below Keyser by about 65 percent, depending on the discharge rate. This over-estimation resulted in a large deaeration coefficient which was artificially compensated for by a large reaeration rate in order to verify the stream data. The coefficients and data as developed by Fuhrman could be used to reflect the conditions in the stream for the given conditions; however, the rates as calculated were not a true measure of the reaeration capability. Calculations of the waste treatment required on the observed rates over-estimated the assimilation capacity by about 300 percent below Keyser, West Virginia.

Another disadvantage of this method is that the stream must be significantly polluted so that there is measurable dissolved oxygen deficit in the stream in all sections for which reaeration rates are required. For predictive algorithms of the flow release model and verification link, the observed method of determining reaeration rates is the most useful as a check on the other two methods.

Predictive Formulations

Streeter and Phelps[1] empirically related the reaeration rate to the depth and velocity stream parameters. Velz[4,5], expanding the concepts of Phelps[66], also developed an empirical method which relates the reaeration rate to the depth and "time of mix" in the stream channel.

In the past decade a considerable amount of research effort has been exerted in developing various formulations for computing the reaeration coefficient based on the physical properties of the stream channel. Using various gas transfer theories, predictive formulations have been proposed by O'Connor and Dobbins[86], Krenkel and Orlob[63], and more recently by Dobbins[13,14]. The formulations relate the reaeration rate to the physical parameters of the stream, such as velocity, depth, slope, longitudinal diffusion, etc.

A statistical approach was taken by Churchill et.al.[63] of the Tennessee Valley Authority (TVA) in investigating various formulations for determining the reaeration rates in the Tennessee Valley. In their studies, they concluded that a simple equation relating the reaeration rate to velocity and depth was adequate to describe the process, and that parameters such as slope and roughness are automatically included in the formulation. A similar approach was taken by Langbein and Durum[87] of the U. S. Geological Survey (USGS) in which the reaeration rate was determined to be primarily a function of velocity and depth.

Gaseous Tracer Techniques

A method for accurately evaluating atmospheric reaeration rate using a radio-active gas tracer has been developed by Tsivoglou et.al.[88]. The technique and the theoretical concepts have been developed in a laboratory with limited field testings. Until the method is more fully proved, its value is rather limited, and the need for a complete evaluation of predictive formulations remains.

Comparison of Methods

To gain insight as to which predictive formulation in general most adequately describes the reaeration process for various streams, a comparison has been made for four different stream reaches. A complete evaluation is beyond the scope of this study; however, due to the sensitivity of the flow release model to the reaeration parameter, the limited comparison is sufficient to illustrate the variations.

The basic data of the four reaches and the reaeration rates calculated by the various methods are presented in Table 15. As can be seen in Table 15, excluding the tracer technique, no one method adequately predicts the reaeration rate in all four of the reaches when compared to the rates calculated from observed data.

The divergence of the O'Connor and Dobbins, TVA, and USGS formulations is readily seen in Figures 13, 14 and 15. In the O'Connor and Dobbins formulation, velocity is raised to the 0.5 power, thereby reducing the sensitivity of the reaeration rate to the velocity term. The TVA and USGS formulations, with velocity raised to the 0.969 and 1.0 powers, respectively, yield a greater sensitivity, especially at the shallower depths.

Computed DO, BOD and temperature profiles for the North Branch of the Potomac River are presented in Figure 16. The DO profiles were computed using the TVA and O'Connor reaeration formulations. The effect of cross-section transformation and a depth-factor is also shown. This will be covered in detail in the next two sections of the appendix.

USE OF PREDICTIVE FORMULATIONS

Before any one of the prediction formulas can be used basin-wide, it will probably be necessary to adjust the reaeration coefficients to make them similar to the values computed from observed data. The adjustment can be applied to over-all formulations or to one of the constituent parameters such as velocity or depth.

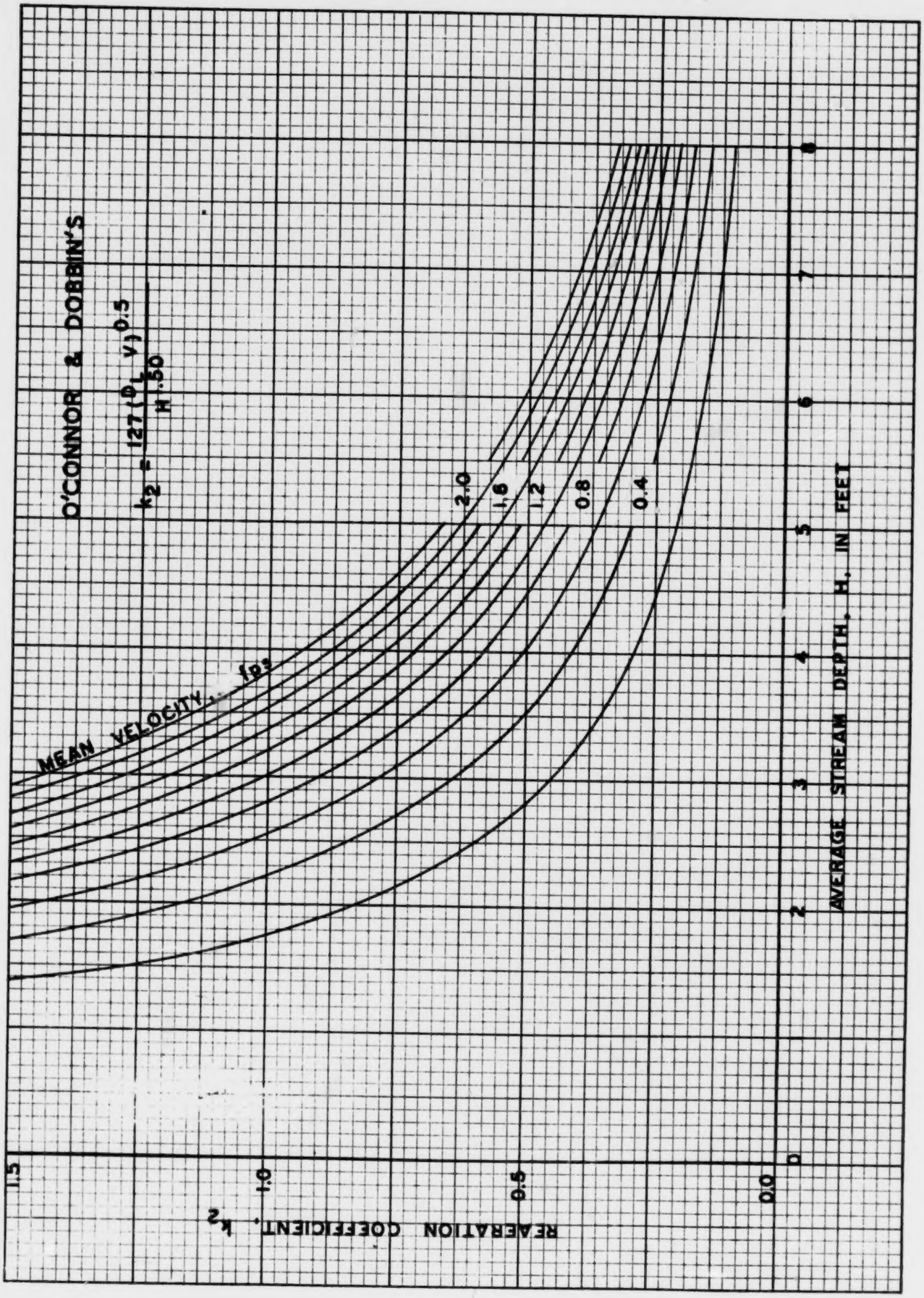

O'CONNOR & DOBBIN'S
$k_2 = \frac{127 (D_L V)^{0.5}}{H^{1.50}}$
MEAN VELOCITY, fps
2.0
1.6
1.2
0.8
0.4
AVERAGE STREAM DEPTH, H, IN FEET
0
2
3
4
5
6
7
8
REAERATION COEFFICIENT, k_2
1.5
1.0
0.5
0.0

Figure 13

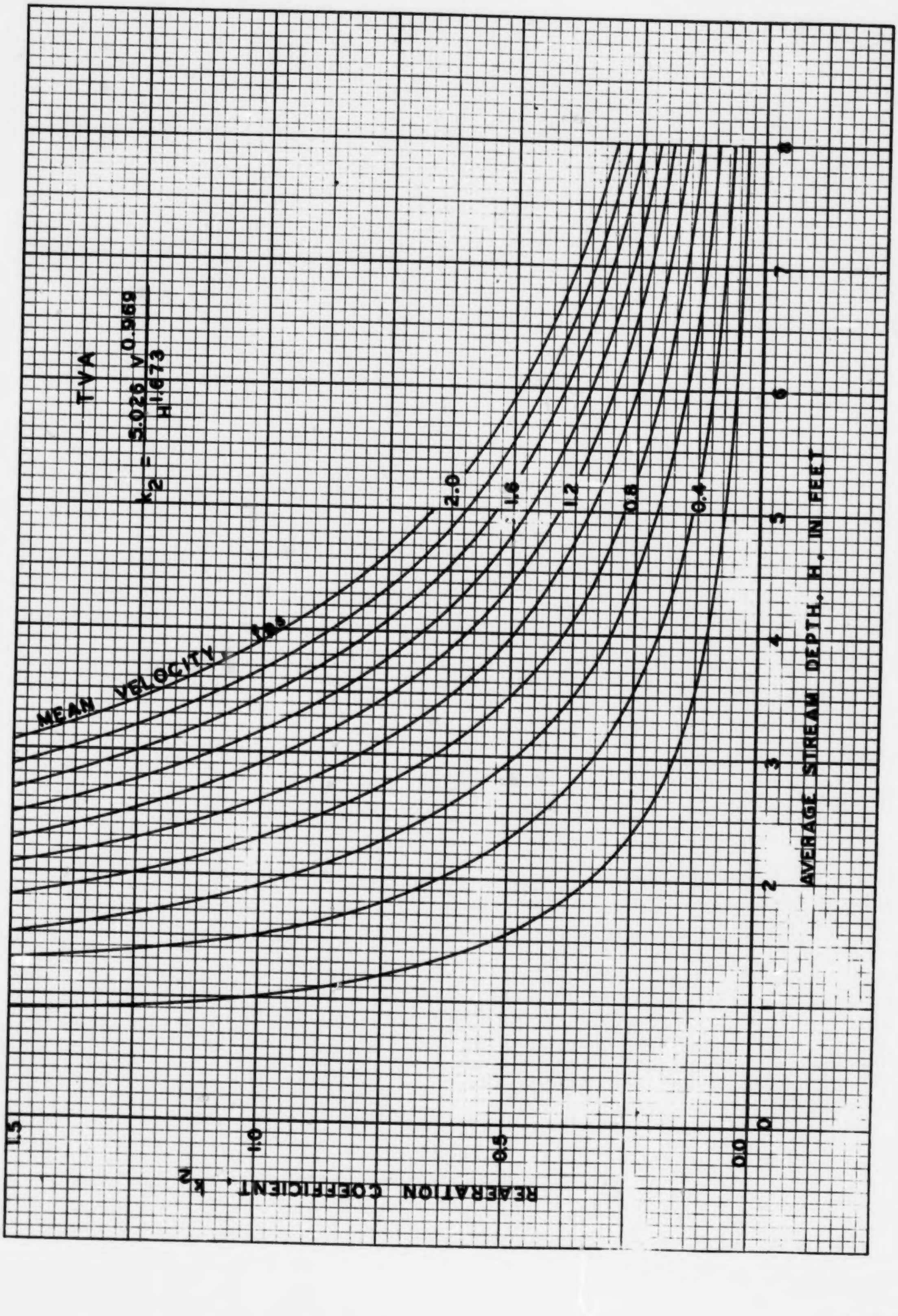

TVA
$k_2 = \frac{5.026\ V^{0.969}}{H^{1.673}}$
MEAN VELOCITY, fps
2.0
1.6
1.2
0.8
0.4
AVERAGE STREAM DEPTH, H, IN FEET
0
2
3
4
5
6
7
8
REAERATION COEFFICIENT, k_2
1.5
1.0
0.5
0.0

Figure 14

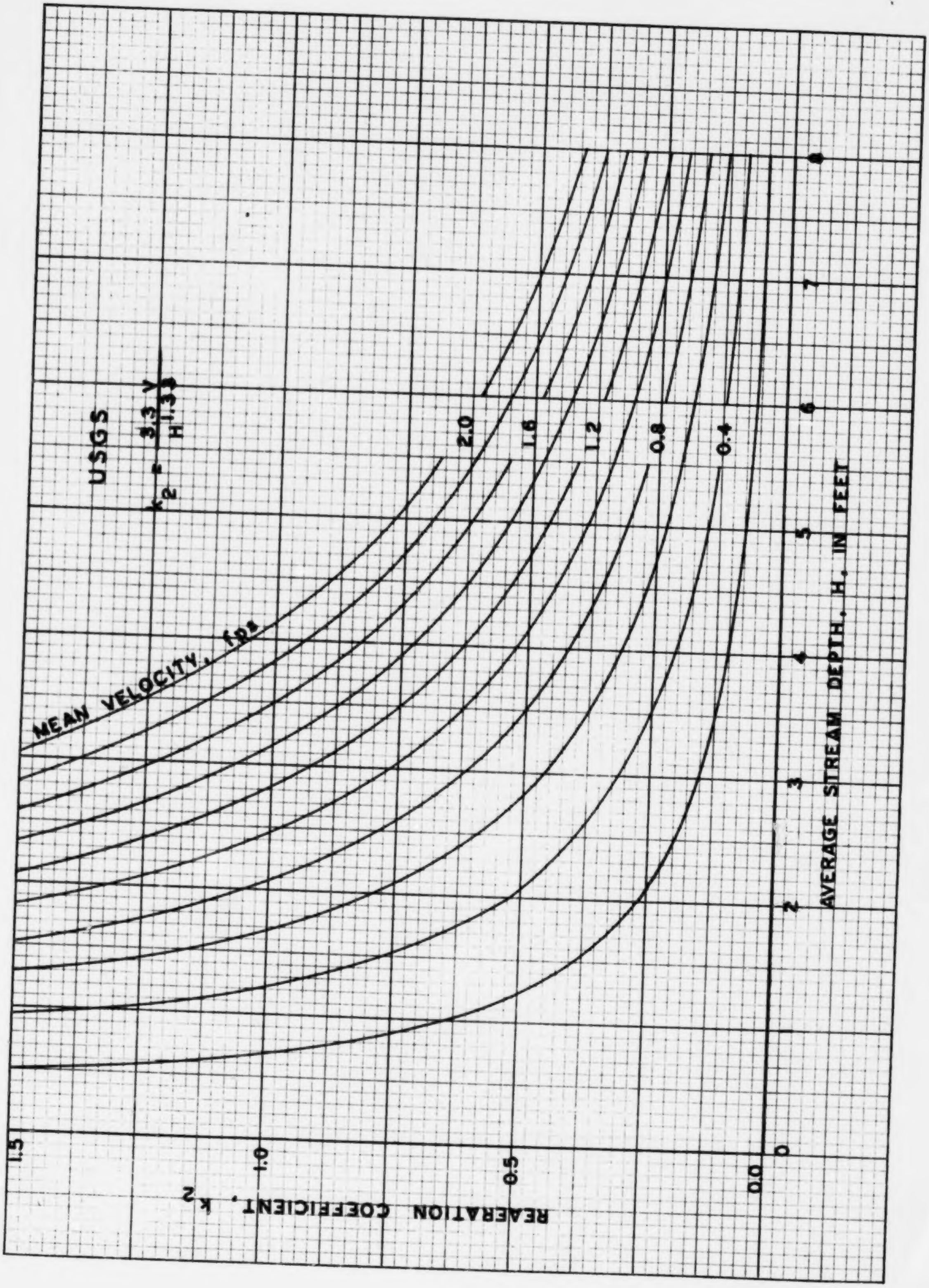

USGS
k2 = 3.3 V / H^1.33
MEAN VELOCITY, fps
2.0
1.6
1.2
0.8
0.4
AVERAGE STREAM DEPTH, H, IN FEET
0
2
3
4
5
6
7
8
REAERATION COEFFICIENT, k2
1.5
1.0
0.5
0.0

Figure 15

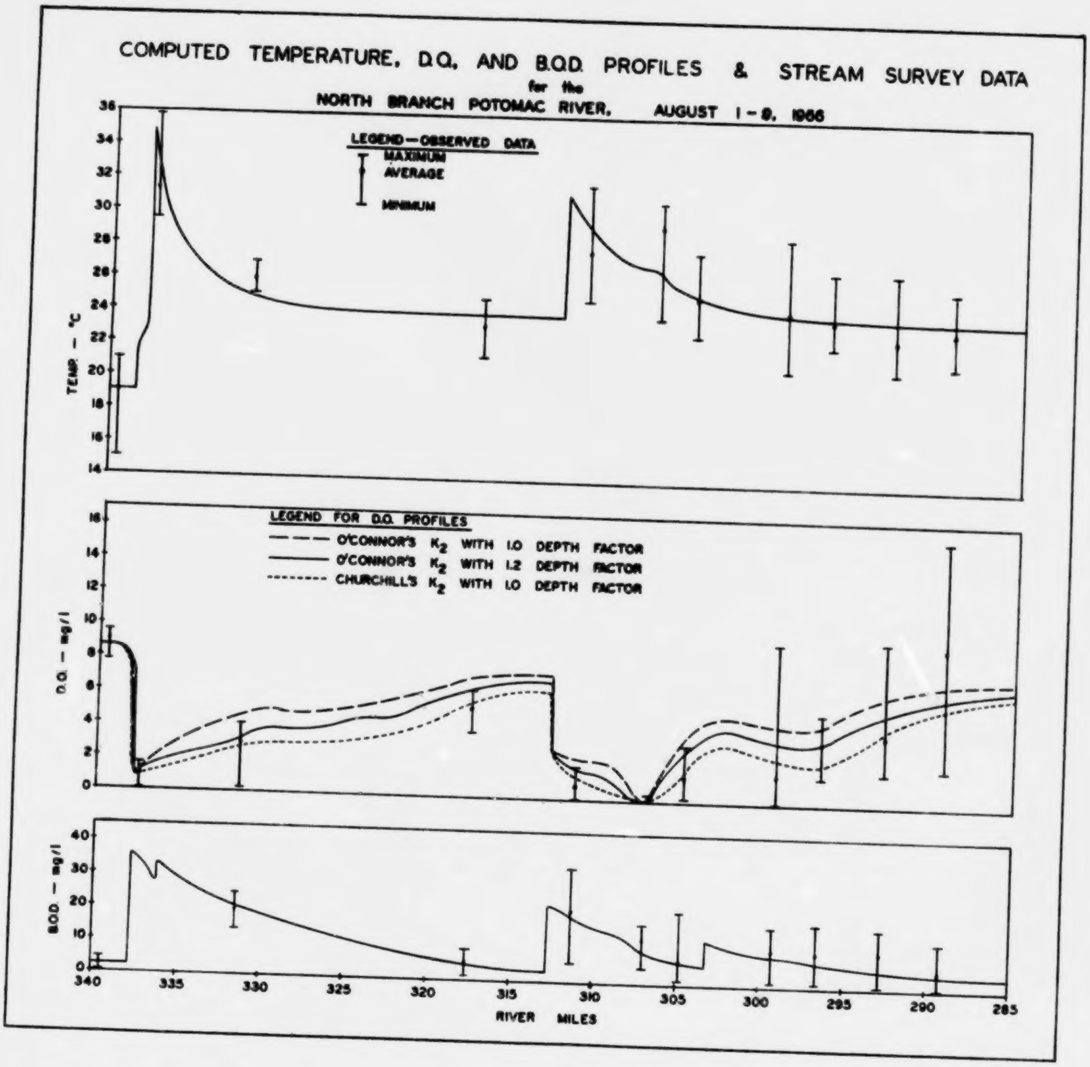

COMPUTED TEMPERATURE, D.O., AND B.O.D. PROFILES & STREAM SURVEY DATA
for the
NORTH BRANCH POTOMAC RIVER, AUGUST 1 - 8, 1966
LEGEND — OBSERVED DATA
MAXIMUM
AVERAGE
MINIMUM
TEMP. — °C
36
34
32
30
28
26
24
22
20
18
16
14
LEGEND FOR D.O. PROFILES
O'CONNOR'S K2 WITH 1.0 DEPTH FACTOR
O'CONNOR'S K2 WITH 1.2 DEPTH FACTOR
CHURCHILL'S K2 WITH 1.0 DEPTH FACTOR
D.O. — mg/l
16
14
12
10
8
6
4
2
0
B.O.D. — mg/l
40
30
20
10
0
340
335
330
325
320
315
310
305
300
295
290
285
RIVER MILES

Figure 16

Table 15

COMPARISON OF REAERATION RATES

Basic Reach Data

Area	Depth (ft)	Flow (cfs)	Velocity (fps)	Slope (ft/ft)	Observed k_2 (1/day)
Upper Patuxent River (Wildlife Refuge)	1.34	11.0	0.24	0.00038	0.28
Lower Patuxent River (Near Hardesty)	1.89	25.0	0.24	0.00019	0.20
North Branch Potomac (Above Pinto)	1.98	100.0	0.41	0.00128	0.94
Jackson River (Below Covington, Va.)	2.00	100.0	0.54	0.00189	1.70

Reaeration Rates*

Method	Upper Patuxent	Lower Patuxent	North Branch	Jackson River
O'Connor and Dobbins	1.58	0.89	1.20	1.27
Churchill	0.77	0.44	0.65	0.80
USGS	0.53	0.34	0.55	0.65
Dobbins	1.50	0.90	2.00	2.15
Gas	ND**	ND	ND	1.50
Observed (Calculated)	0.28	0.20	0.94	1.70

* All values base ten

** Not determined

Of the formulations investigated in the pilot study of the Patuxent Basin, the TVA relationship appeared to describe the reaeration process best. However, it was still necessary to adjust the coefficient to make the computed DO profiles similar to the observed profile.

Various methods for adjusting the TVA formulation were investigated. Assuming the constants and exponents of the TVA formulation to be valid, and establishing the time-of-travel by dye studies, the only parameter left to adjust was the depth. Further, after examining the cross-section data from the Patuxent Basin, the rectangular transformation appeared to yield a too low mean stream depth. (See next section.)

A series of computer runs was made in which the mean depth was increased linearly by a depth-factor until the computed profiles compared favorably to the observed data. The depth-factor was then used in verifying observed data from other independent stream surveys, and the calculated profiles were very similar to the observed profiles. A similar approach was used for the Potomac Basin.

As can be seen in Figure 16, the DO profile computed using the Churchill formulation with no depth-factor appears to match the observed data. With a depth-factor of 1.2, the DO profile computed using the O'Connor formulation also appears to be satisfactory. The choice as to which formulation to use is dictated primarily by which formulation in general best describes the reaeration process for the entire basin.

Prior to the use of any factor, it is necessary to analyze the field data carefully and delineate, manually or, if sufficient data is available by spectral analysis, any periodicity in the survey data. For example, a tremendous diurnal DO fluctuation was observed in the lower reaches of the North Branch, as also can be seen in Figure 16. Average DO values were used for model verification.

More research effort is required to either develop a more general formulation and/or methods for systematically adjusting the known methods.

CROSS-SECTION DATA

As indicated in the previous sections, most of the formulations for predicting the reaeration process in streams are dependent upon a depth-of-stream parameter. The depth of a stream cross-section is usually defined as area/top width. Implicit in this definition is a rectangular transformation of the stream cross-section.

From over 100 cross-sections of the Patuxent and Potomac Rivers, it appears that the stream is consistently more parabolic than rectangular. The problem is, "what is the depth of a non-rectangular section?" Furthermore, the velocity of the stream is usually greater in the deeper parts of the cross-section.

Three methods for cross-section transformation, excluding inspection, are given below:

I Rectangular transformation

$$\text{depth} = \frac{\Sigma\ \omega * d}{\Sigma\ \omega} = \frac{A}{W}$$

II Moments of depth proportional to discharge

$$\text{depth} = \frac{\Sigma\ \omega * d * v * d}{\Sigma\ \omega * d * v} = \frac{\Sigma\ q*d}{Q}$$

III Moments of depth proportional to area

(assuming $v_1 = v_2 = v_3 \ldots v_n$)

$$\text{depth} = \frac{v*\Sigma\ \omega*d*d}{v*\Sigma\ \omega * d} = \frac{\Sigma\ \omega*d^2}{\Sigma\ \omega*d} = \frac{\Sigma\ \omega * d^2}{A}$$

where

w = width of an increment of the cross-section

d = average depth of an increment of the cross-section

v = mean velocity of an increment of the cross-section

q = discharge of an increment of the cross-section

W = total width of cross-section

Q = total discharge of cross-section

A = total area of cross-section

A comparison of the three transformations was made for a limited number of cross-sections in the coastal area of the Patuxent Basin and in upstream portions of the Potomac Basin. From cross-sectioning data in the Patuxent Basin, the mean depths as computed by method III were about 15 to 25 percent greater than method I; while in the Potomac Basin, method III yielded a mean depth about 10 to 15 percent greater than method I. At USGS gaging stations, method II and III were both about 10 percent greater than method I.

With the limited number of cross-sections with velocity measurements, a statistical comparison cannot be made; however, results tend to indicate that a rectangular transformation does not yield a representative mean depth, especially in coastal streams such as the Patuxent. Moreover, if the area transformation is similar to the discharge transformation, considerable saving in field work can be realized.

Another problem in interpreting cross-section data is the variability in depth along the longitudinal profile and the possibility of bias on the part of the field personnel in selecting cross-section points. For a given geographically homogeneous reach of stream channel in the Patuxent and Potomac Rivers, the distribution of depth has been found to be normal.

See Figure 17 for variations in depth in the North Branch of the Potomac. O'Connor[9] also reported a normal distribution of depth in his studies of the Wabash Clarion, and Codorus Basins.

Assuming a normal distribution, it is possible to determine statistically the number of cross-sections needed to assure a given probability that the measured mean value will represent the true mean. While it is possible to determine the number of cross-sections required, the reaeration rate, which is a function of depth to a power, may not be normally distributed and statistically less significant.

In a ten-mile reach of the North Branch of the Potomac River below Keyser, the reaeration rate was calculated from fifty-two cross-section points using the O'Connor and Dobbins formulations. As also can be seen in Figure 17, the reaeration rate for this reach has a skewed distribution.

While the point calculations introduce an additional bias in the velocity term, the pronounced skewness in the reaeration rate for the reach is indicative of some of the problems in data interpretation. Some of the variability in the predictive formulations may be due to the interpretation of the cross-section data and the aggregation of sections for a given stream reach. Incorporated in the suggested research effort in the reaeration study should be comprehensive field testing, including a detailed analysis of cross-section transformations.

BOD MECHANISMS AND FACTORS

Using a first order reaction, the calculated BOD concentrations for long, relatively unpolluted stretches of the Potomac River tend to approach 0.0 mg/l of BOD, with resulting DO values near 100 percent of saturation. Field BOD measurements in these reaches normally range from 1.0 to 3.0 mg/l, with DO levels about 80 to 90 percent of saturation.

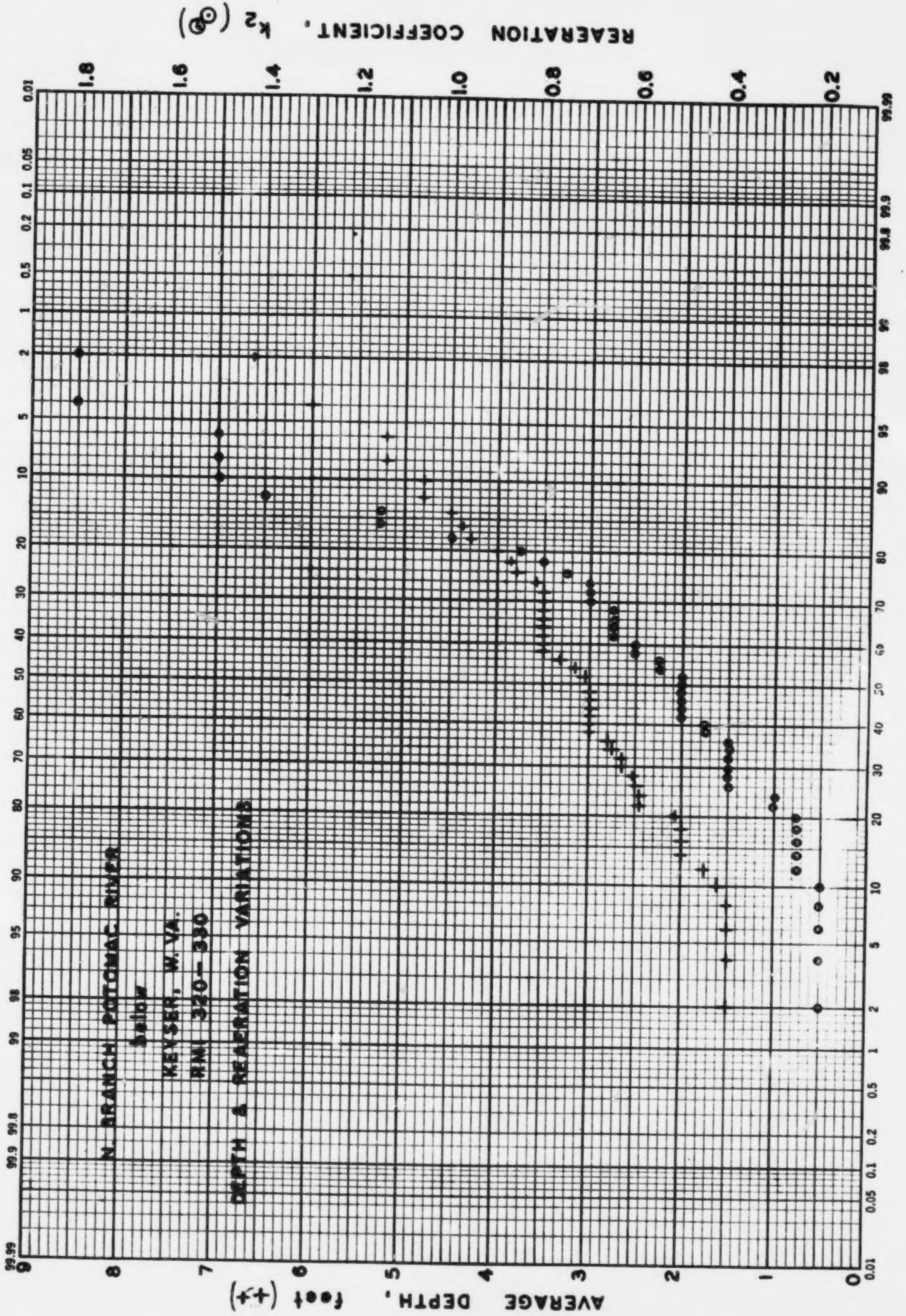

REAERATION COEFFICIENT, k_2 (⊙)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
AVERAGE DEPTH, feet (+)
9
8
7
6
5
4
3
2
1
0
N. BRANCH POTOMAC RIVER
below
KEYSER, W. VA.
RM 320 – 330
DEPTH & REAERATION VARIATIONS

Figure 17

Similar observations were made by Hall[89] in his work on the James River, a sister basin to the Potomac.

It appears that various not-readily-quantifiable sources and sinks of oxygen such as bank loads, nitrification, scouring, etc. result in a dynamic-equilibrium level for BOD of about 2.0 mg/l. Associated with this 2.0 mg/l of BOD dynamic-equilibrium is a depressed DO level of about 80 to 90 percent of saturation.

Two methods for coping with this problem are (1) inclusion of all sources and sinks of oxygen in the quality algorithms, or (2) the setting of a minimum value for the BOD dynamic-equilibrium level. Since technological developments at the present time are either not adequate or too costly to completely quantify all sources and sinks, the latter approach has been used in the quality algorithms.

In the verification link and flow release models, whenever the BOD concentration decays below a prescribed level (read in as input data), it is reset to the prescribed level after the oxygen uptake for the given section has been computed. BOD and DO profiles obtained from computer runs of the verification link appear to be similar to observed profiles developed from field data.

A PREDICTIVE MODEL FOR PHOSPHATES

As indicated in Chapter VI, high concentrations of nutrients and the resulting algal blooms are becoming an increasing problem in water quality management. One method for reducing the algal problem is to maintain a phosphate concentration in the stream below the minimum threshold limits for an algal bloom.

Studies in the Patuxent River Basin indicate a large portion of phosphates coming from waste treatment plants are being lost to plants,

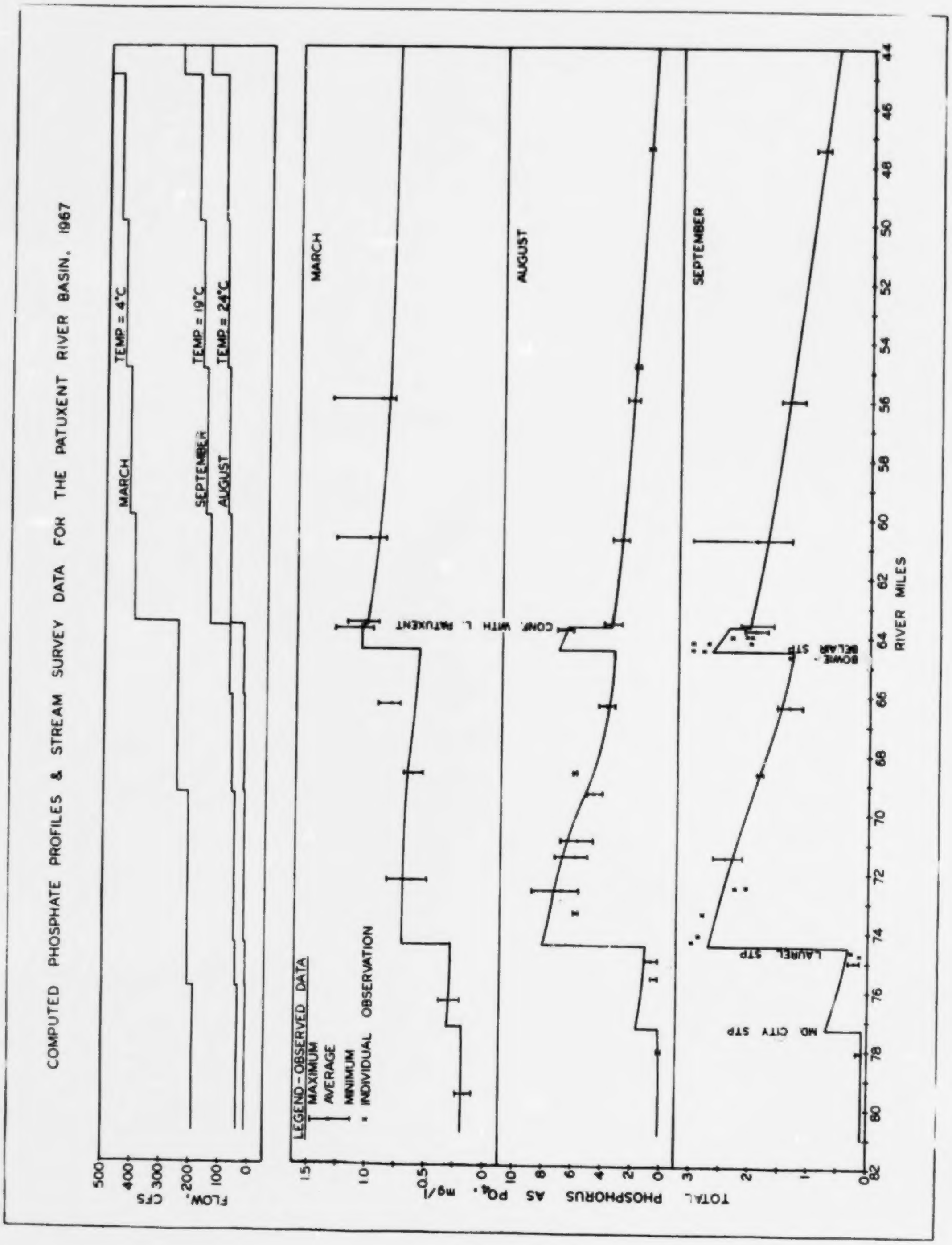

COMPUTED PHOSPHATE PROFILES & STREAM SURVEY DATA FOR THE PATUXENT RIVER BASIN, 1967
FLOW, CFS
500
400
300
200
100
0
MARCH
TEMP = 4°C
SEPTEMBER
TEMP = 19°C
AUGUST
TEMP = 24°C
TOTAL PHOSPHORUS AS PO4, mg/l
1.5
1.0
0.5
0
10
8
6
4
2
0
3
2
1
0
LEGEND - OBSERVED DATA
MAXIMUM
AVERAGE
MINIMUM
• INDIVIDUAL OBSERVATION
MARCH
AUGUST
SEPTEMBER
CONF. WITH L. PATUXENT
BOWIE - BELAIR STP
LAUREL STP
MD. CITY STP
RIVER MILES
82
80
78
76
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44

Figure 18

stream bed, etc. In analyzing data from the Patuxent, it appears that the loss of phosphates can be mathematically approximated by a first order reaction similar to that of a biologically degradable waste. An algorithm for modeling the loss of phosphates based on the first order reaction is included in the verification link, and provisions are made for inclusion into the flow release model.

Computed and observed profiles for three studies are presented in Figure 18. The loss rate appears to be a function of temperature and flow, with values ranging from 0.1 to 0.2.

More field studies are required to determine how stationary the loss of phosphates is throughout an annual cycle. If the loss rate is predictable, the model could be used to determine phosphate treatment requirements and/or incorporate into the flow release model as indicated in Chapter VII.

TIME OF TRAVEL

Of all the parameters required in the model, the most basic and significant is the travel time. As indicated in Appendix B, the cost of the time-of-travel studies range from about $50 to $100 per mile. Preliminary studies indicate that gaging station data in conjunction with limited dye studies can reduce this cost considerably.

As presented in Chapter III, the velocity at a given cross-section can be expressed mathematically as:

$$\text{Velocity} = CC \times (\text{Flow})^{DD}$$

For most gaging stations in the Potomac Basin, the value of exponent "DD" ranges from .300 to .500 with constant "CC" fluctuating more, depending on flow.

The quality relationship being time dependent requires the time-of-travel between two points rather than the velocity at a given point. By assuming (1) that time-of-travel and flow can be expressed similarly to the velocity at a cross-section, and (2) that exponents are equal, a considerable amount of effort and money can be saved.

For a 7.8 mile of geographically homogeneous reach of the Patuxent River, four time-of-travel studies were conducted at four different flow rates. As can be seen in Figure 19, the velocity versus flow and time-of-travel versus flow relationships are essentially parallel.

If, in general, the two slopes are parallel, only one time-of-travel study will be required in reaches where velocity versus flow relationship is known. More field studies will be needed in various geographical situations, especially in impoundments, before general relationships can be statistically extracted.

Analogous to time-of-travel and velocity relationships, a similar approach can be taken for the mean depth at given cross-section sites and average depth relationships. Here again, more field work is required to establish the limits of the relationships.

The cost of conducting one time-of-travel study and obtaining cross-sections for the 894 miles on the Potomac River Basin model is about $130,000. If the general relationships can be firmly established, considerable expenditures of money can be saved in some of the field studies required in model verification.

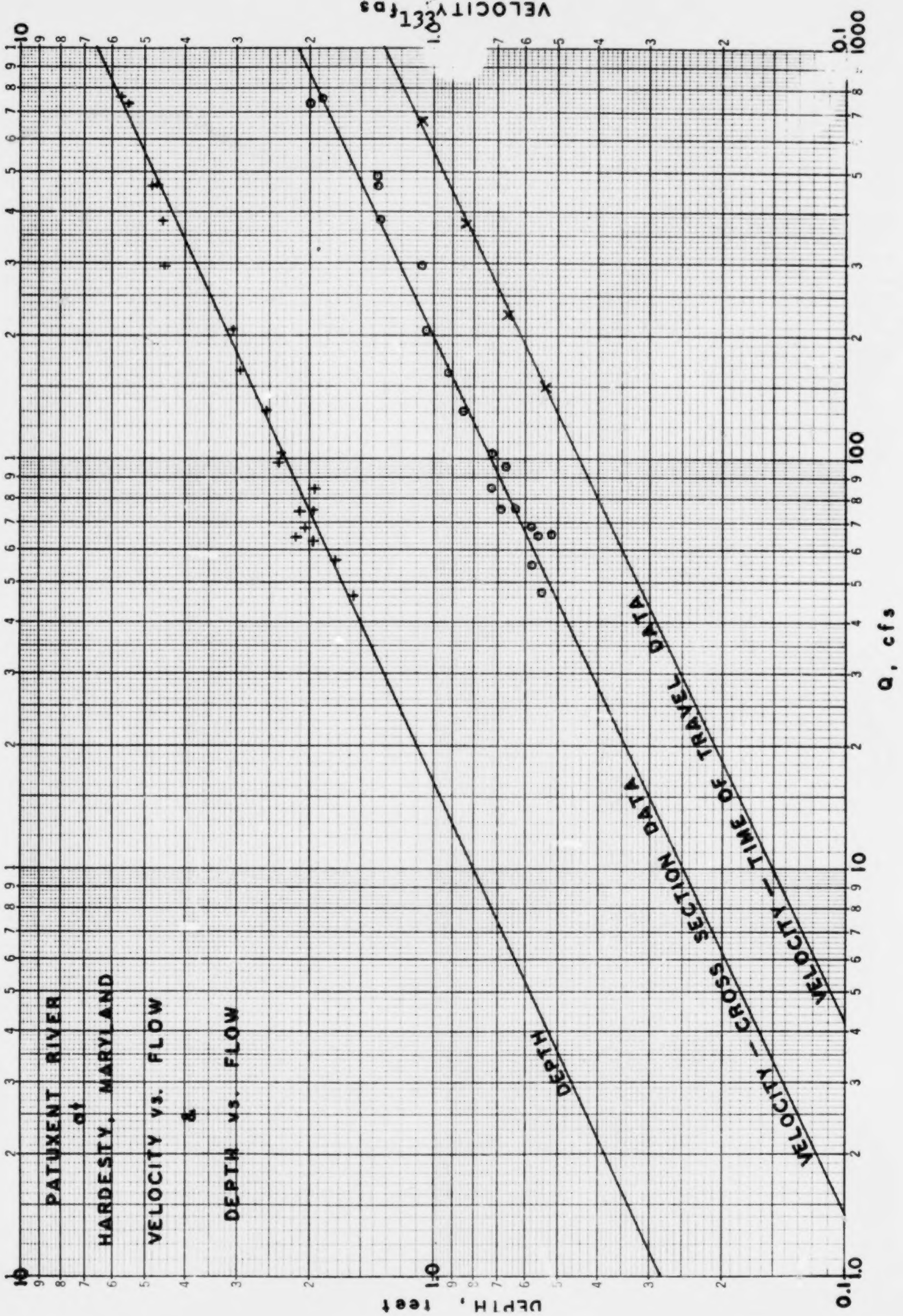

PATUXENT RIVER
at
HARDESTY, MARYLAND
VELOCITY vs. FLOW
&
DEPTH vs. FLOW
DEPTH
VELOCITY — CROSS SECTION DATA
VELOCITY — TIME OF TRAVEL DATA
DEPTH, feet
VELOCITY, fps
Q, cfs
1.0
10
100
1000
0.1
1.0
10

Figure 19

A PROCEDURE FOR VERIFICATION OF THE QUALITY FORMULATIONS

Based on the experience in the Patuxent Basin, a method for implementing the flow release model has been developed according to the following format.

1. Define the physical system including an inventory of all wastewater discharges and water intakes.
2. Establish the stream channel characteristics.
3. Partition the river basin and determine all parameters, constants, etc.
4. Verify the physical and quality formulations.

The above format provides for a systematic development of the data, thus reducing the chance for error; it can also be used to indicate data voids.

Defining the Physical System

A detailed inventory of wastewater discharges, water intakes, dams, and other topographic features is necessary to define the system. Included in the data requirements are wastewater quality and quantity, water withdrawals, stream flow quality and quantity, river mile indexing, drainage area, etc. Knowledge of the basin area and engineering judgment are essential for definition of the system.

Establishing Stream Channel Characteristics

For all stream flow gaging stations, data required to establish velocity-flow and depth-flow relationship can be obtained from the United States Geological Survey. The data are obtained each time a station is rated by the Survey.

Depth relationships for additional points can be obtained by cross-sectioning the stream at two different stream flows. Similarly, a greater number of sections can be rated and more velocity relationships established. A method of relating time-of-travel to velocity and statistical analysis of cross-section data is given in this appendix.

Basin Partitioning and Parameter Determinations

Partitioning of the basin and the determination of various parameters, constants, etc., are two of the most important steps for implementation of the model. To expedite the study, the following procedure has been established for a given reach of stream.

1. Plot the longitudinal profile of the stream.
2. Section the reach into segments according to instructions given in the section on the descriptive paragon.
3. Partition similar segments, according to channel characteristics.
4. By segments, plot the drainage area profile.
5. By segments, plot the base stream flow (such as 7-day low flow with a recurrence interval once in 10 years).
6. From time-of-travel data, plot by segments a velocity profile for the base flow.
7. From cross-section data, plot by segments a depth profile for the base flow.
8. Number the nodes and evaluate the constants and exponents for each segment.

Verification of Quality Formulations

Good stream survey data are vital to validation of the quality formulations. By plotting the isopleths of the quality data, diurnal fluctuations can be observed and quantized. These plots are also useful in reducing the survey data to steady-state conditions and in checking the time-of-travel determinations.

Having reduced the data and plotted the stream quality profiles, the coefficients of the formulations have to be adjusted until the calculated and observed profiles are similar. The procedure given below has been developed for the verification process.

1. Check and correct if necessary the calculated depth and velocity profiles.
2. Compare the calculated temperature profiles with the field data, and if necessary adjust the temperature coefficient.
3. From existing quality data and isopleth plots determine the deaeration coefficients for the various stream reaches.
4. Compare the calculated BOD profiles with the survey data, and where necessary adjust the deaeration coefficient.
5. Whenever necessary the depth-factor constants for each segment are adjusted so that calculated and observed DO profiles are similar.

Due to the dependence of the parameters and coefficients upon those in the preceding step, the order of development and verification as given in the above procedure is important. For example, both the BOD and DO quality formulations are temperature dependent. Therefore, it is a necessity to have a well defined temperature algorithm before one attempts to verify the BOD and DO formulations.

APPENDIX B

MODEL DATA FOR THE POTOMAC RIVER BASIN

Reduced listings of the Potomac River Basin basic data used in the flow release model are exhibited in this appendix. Since numerous computer runs have been made under various conditions, it is not feasible to include all of the input data. The various data inputs are linked by the descriptive paragon as described in Chapter III.

Detailed schematics of individual stream reaches of the Basin, showing all major waste discharges, water intakes, gaging stations, impoundments, etc., are displayed in Figures 20 through 29. An overall general schematic of the Potomac River Basin system is presented in Figure 30.

For 81 nodes, including the 14 proposed reservoirs, stream flows were accrued as summarized in Table 16. In stream reaches below a terminal source where there are no major tributaries, the incremental flow based on the increase in drainage area has been introduced into the system at add points. Unregulated tributaries not receiving any significant waste loads or used for water supply have been indexed similar to add points.

In the non-tidal portion of the Basin, there are over 200 surface-water supplies and waste-water discharges. For this study all surface-water supplies with an intake rate greater than 0.5 mgd and all waste-water discharges with a flow greater than 0.5 mgd or population equivalent of 1,000 or greater were included in the model. The surface-water supplies and waste-water discharges used in this study are presented in Table 17.

Current waste treatment levels have been used except in the North Branch area. For the North Branch area, in order to stay within the regulation capacity of the impoundments, the treatment levels for West

Virginia Pulp and Paper Company and Celanese Corporation have been [illegible] [illegible] and 90 percent, respectively. For discharges currently entering the system above the proposed impoundments and for the South River of the South Fork Shenandoah River, the waste loads have been routed as shown in the detailed schematics.

The basic data for the 14 proposed reservoirs are presented in Table 3. Not included are the Seneca Project which has been removed from the recommended plan and the Stony Creek Project which is in series with the Bloomington impoundment. Since there are no significant organic waste loads between the impoundments, and Stony Creek is small when compared to Bloomington, the omission of Stony Creek due to model limitations is not too significant.

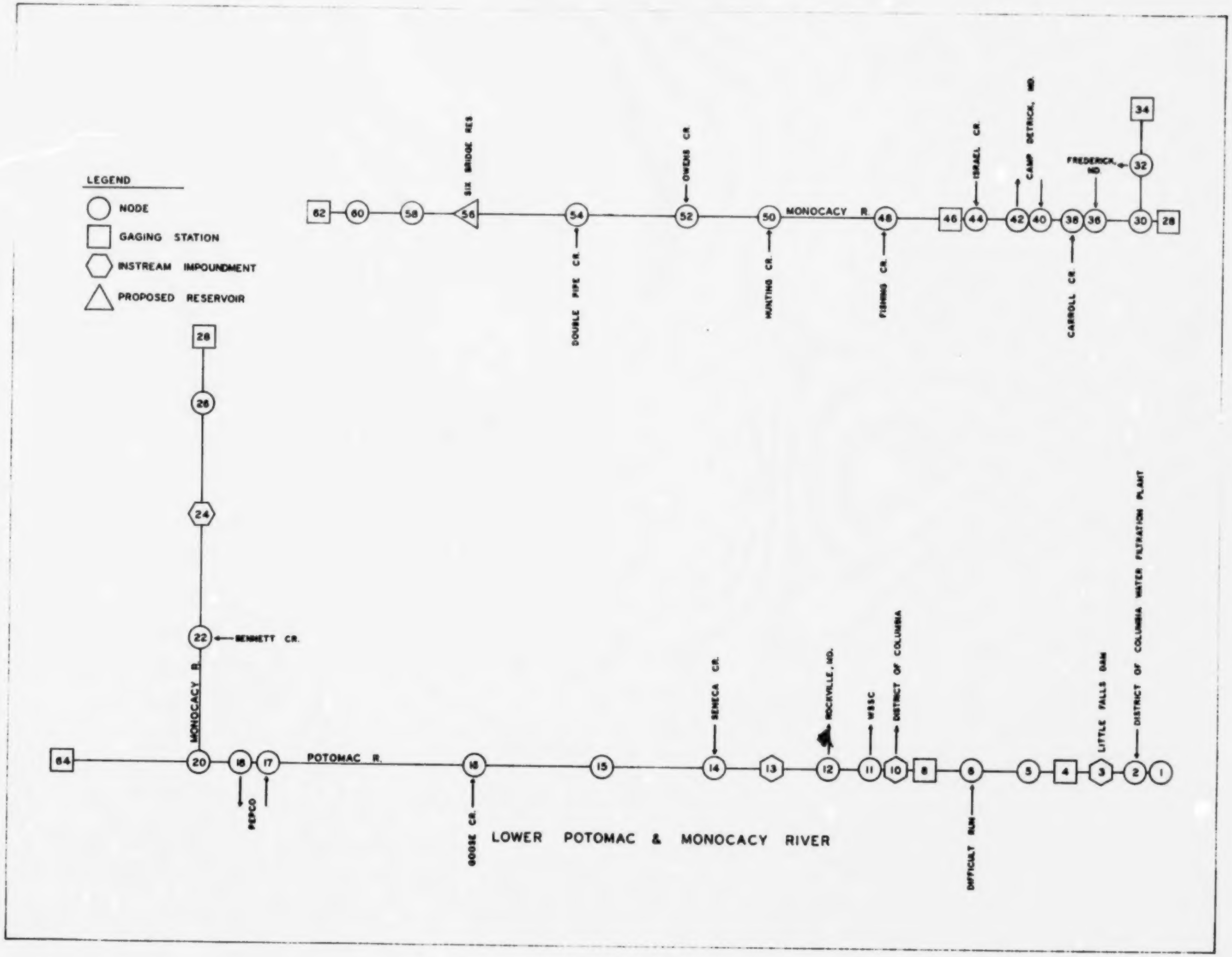

LOWER POTOMAC & MONOCACY RIVER
LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
POTOMAC R.
MONOCACY R.
MONOCACY R.
DISTRICT OF COLUMBIA WATER FILTRATION PLANT
LITTLE FALLS DAM
DIFFICULT RUN
DISTRICT OF COLUMBIA
WSSC
ROCKVILLE, MD.
SENECA CR.
GOOSE CR.
PEPCO
BENNETT CR.
FREDERICK, MD
CARROLL CR.
CAMP DETRICK, MD.
ISRAEL CR.
FISHING CR.
HUNTING CR.
OWENS CR.
DOUBLE PIPE CR.
SIX BRIDGE RES
1
2
3
4
5
6
8
10
11
12
13
14
15
16
17
18
20
22
24
26
28
28
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
62
64

Figure 20

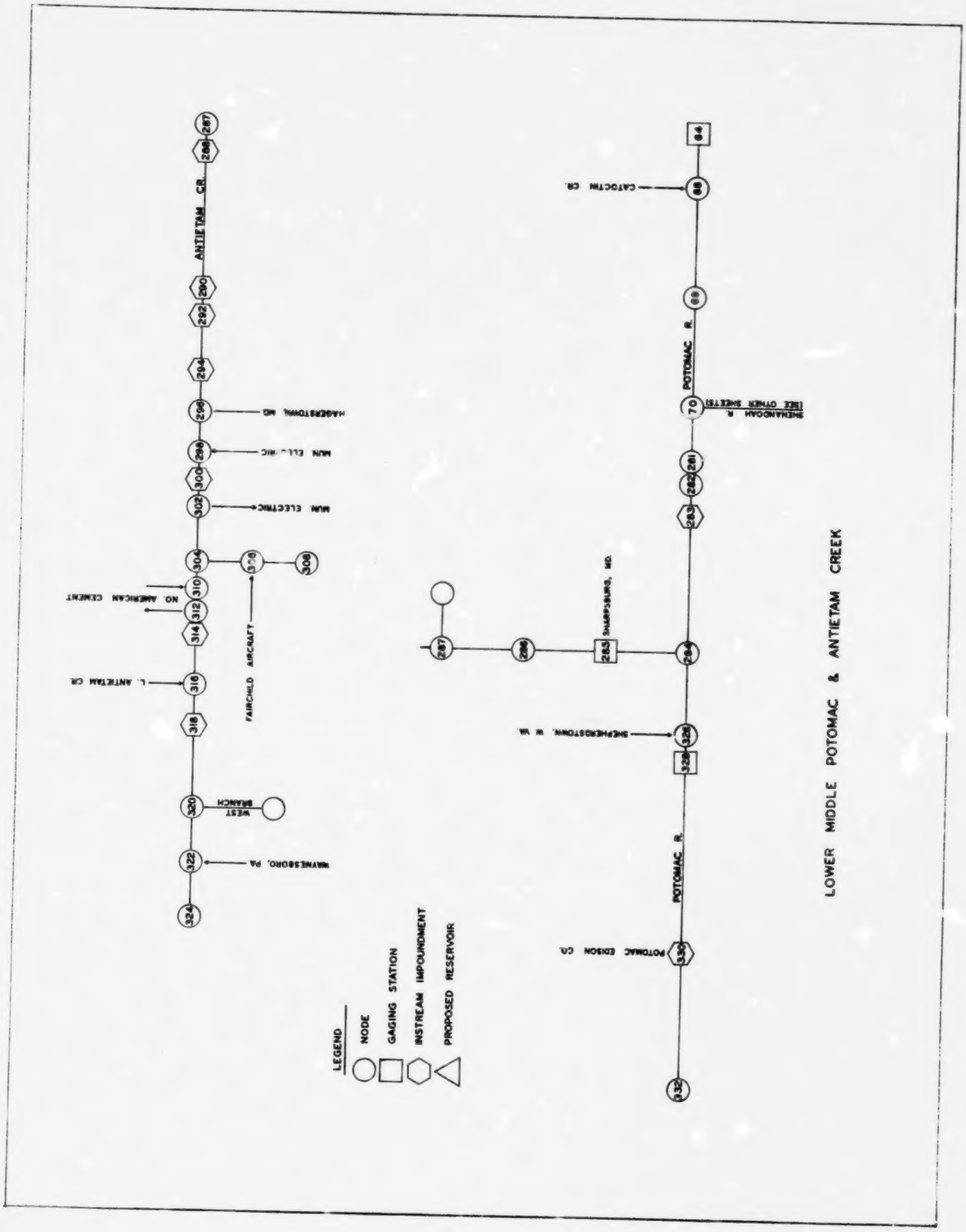

LOWER MIDDLE POTOMAC & ANTIETAM CREEK
LEGEND
○ NODE
□ GAGING STATION
⬡ INSTREAM IMPOUNDMENT
△ PROPOSED RESERVOIR
ANTIETAM CR.
HAGERSTOWN, MD
MUN. ELECTRIC
MUN. ELECTRIC
FAIRCHILD AIRCRAFT
NO. AMERICAN CEMENT
L. ANTIETAM CR.
WEST BRANCH
WAYNESBORO, PA.
CATOCTIN CR.
POTOMAC R.
SHENANDOAH R.
(SEE OTHER SHEETS)
SHARPSBURG, MD.
SHEPHERDSTOWN, W. VA.
POTOMAC R.
POTOMAC EDISON CO.

Figure 21

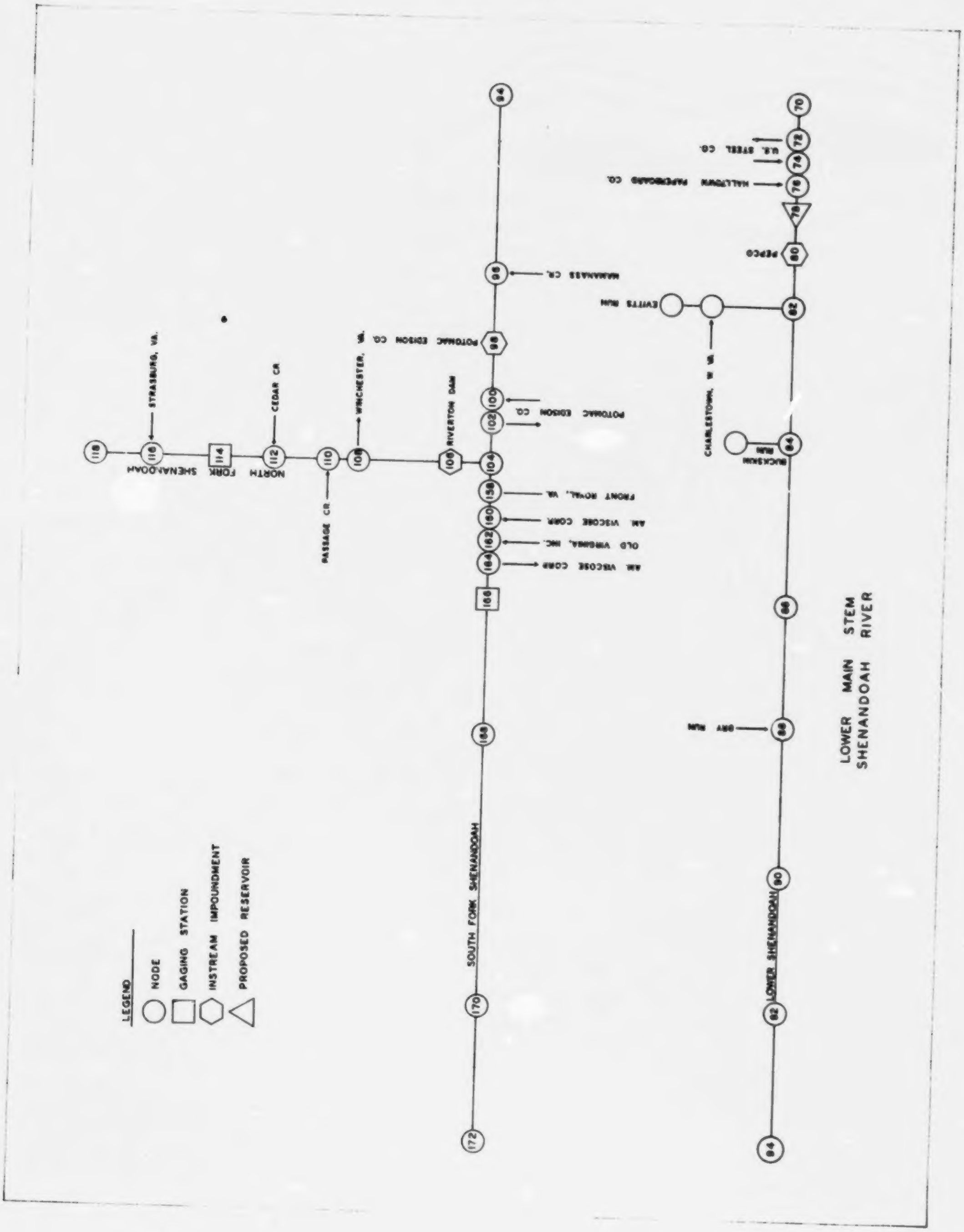

LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
SOUTH FORK SHENANDOAH
172
170
168
166
164
AM. VISCOSE CORP
162
OLD VIRGINIA, INC.
160
AM. VISCOSE CORP.
158
FRONT ROYAL, VA.
104
106
RIVERTON DAM
108
WINCHESTER, VA.
110
PASSAGE CR.
112
CEDAR CR.
NORTH FORK SHENANDOAH
114
116
STRASBURG, VA.
118
102
100
POTOMAC EDISON CO.
98
POTOMAC EDISON CO.
96
MANASSAS CR.
94
LOWER SHENANDOAH
94
92
90
88
DRY RUN
86
84
BUCKSKIN RUN
CHARLESTOWN, W. VA.
82
EVITTS RUN
80
PEPCO
78
76
HALLTOWN PAPERBOARD CO.
74
72
U.S. STEEL CO.
70
LOWER MAIN STEM SHENANDOAH RIVER

Figure 22

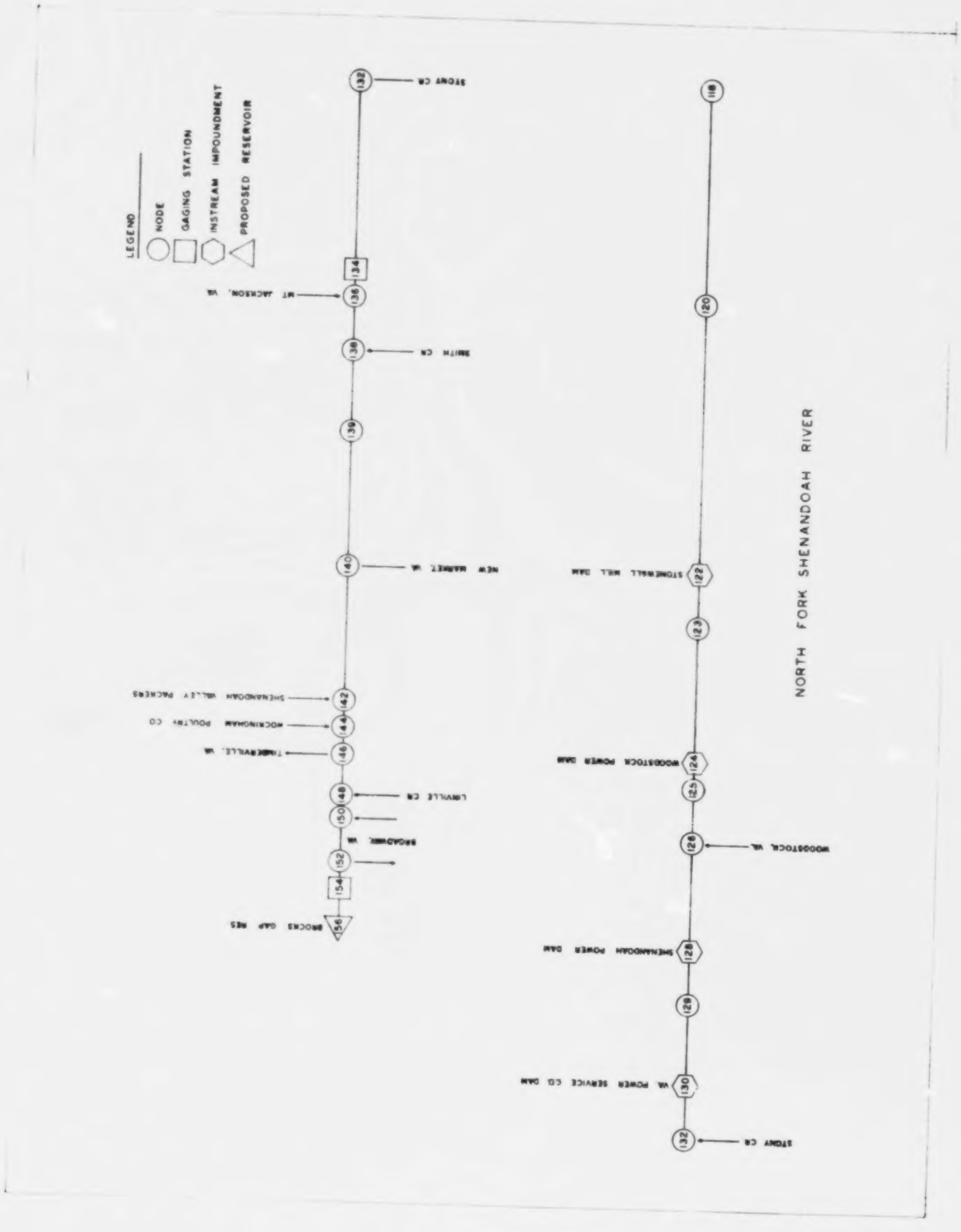

LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
BROCKS GAP RES
156
154
152
BROADWAY, VA
150
148
LINVILLE CR
146
TIMBERVILLE, VA
144
ROCKINGHAM POULTRY CO
142
SHENANDOAH VALLEY PACKERS
140
NEW MARKET, VA
139
138
SMITH CR
136
MT JACKSON, VA
134
132
STONY CR
132
STONY CR
130
VA POWER SERVICE CO DAM
129
128
SHENANDOAH POWER DAM
126
WOODSTOCK, VA
125
124
WOODSTOCK POWER DAM
123
122
STONEWALL MILL DAM
120
118
NORTH FORK SHENANDOAH RIVER

Figure 23

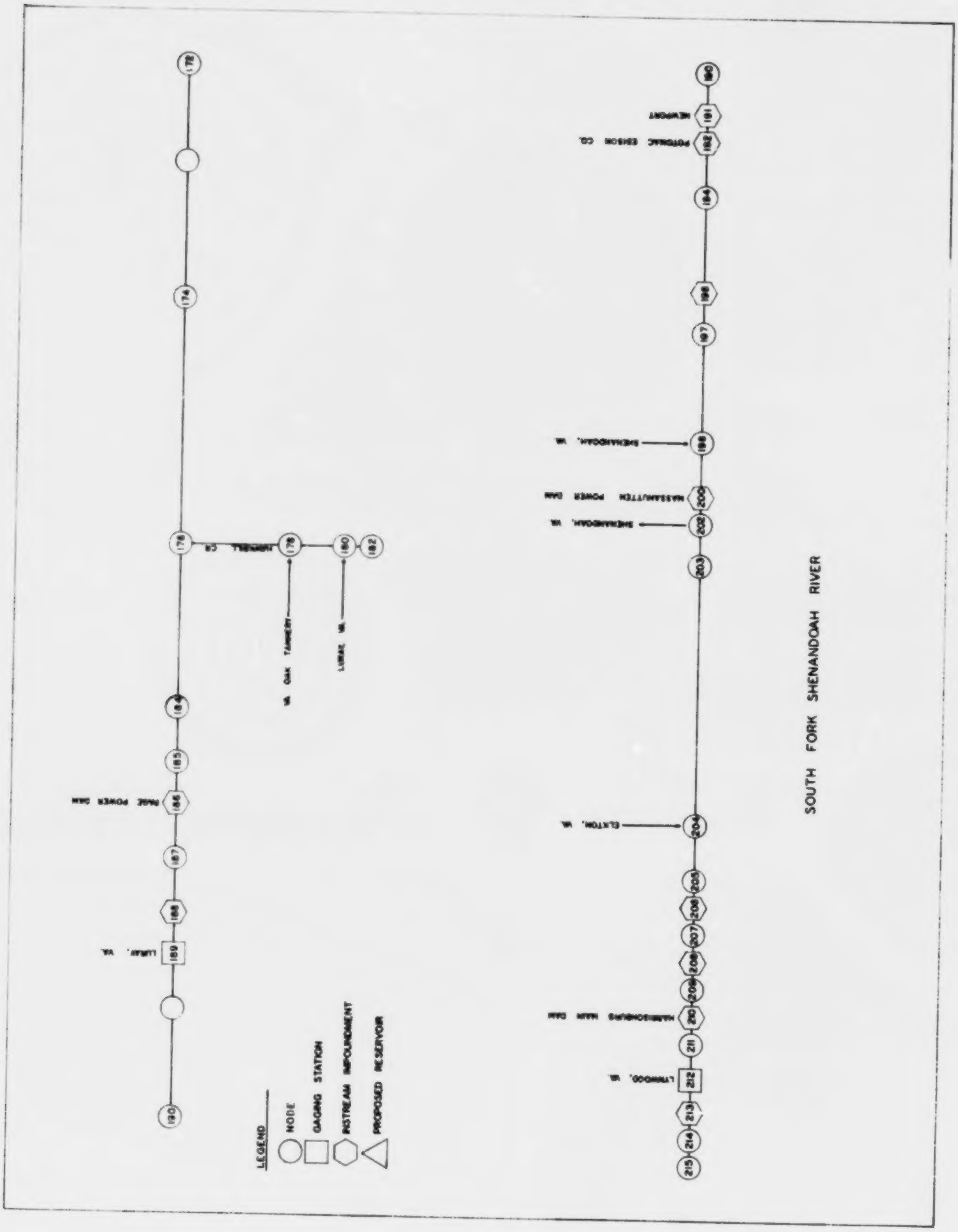

LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
HAWKSBILL CR
VA. OAK TANNERY
LURAY VA.
PAGE POWER DAM
LURAY, VA.
NEWPORT
POTOMAC EDISON CO.
SHENANDOAH, VA.
MASSANUTTEN POWER DAM
SHENANDOAH, VA.
ELKTON, VA.
HARRISONBURG MAIN DAM
LYNWOOD, VA.
SOUTH FORK SHENANDOAH RIVER

Figure 24

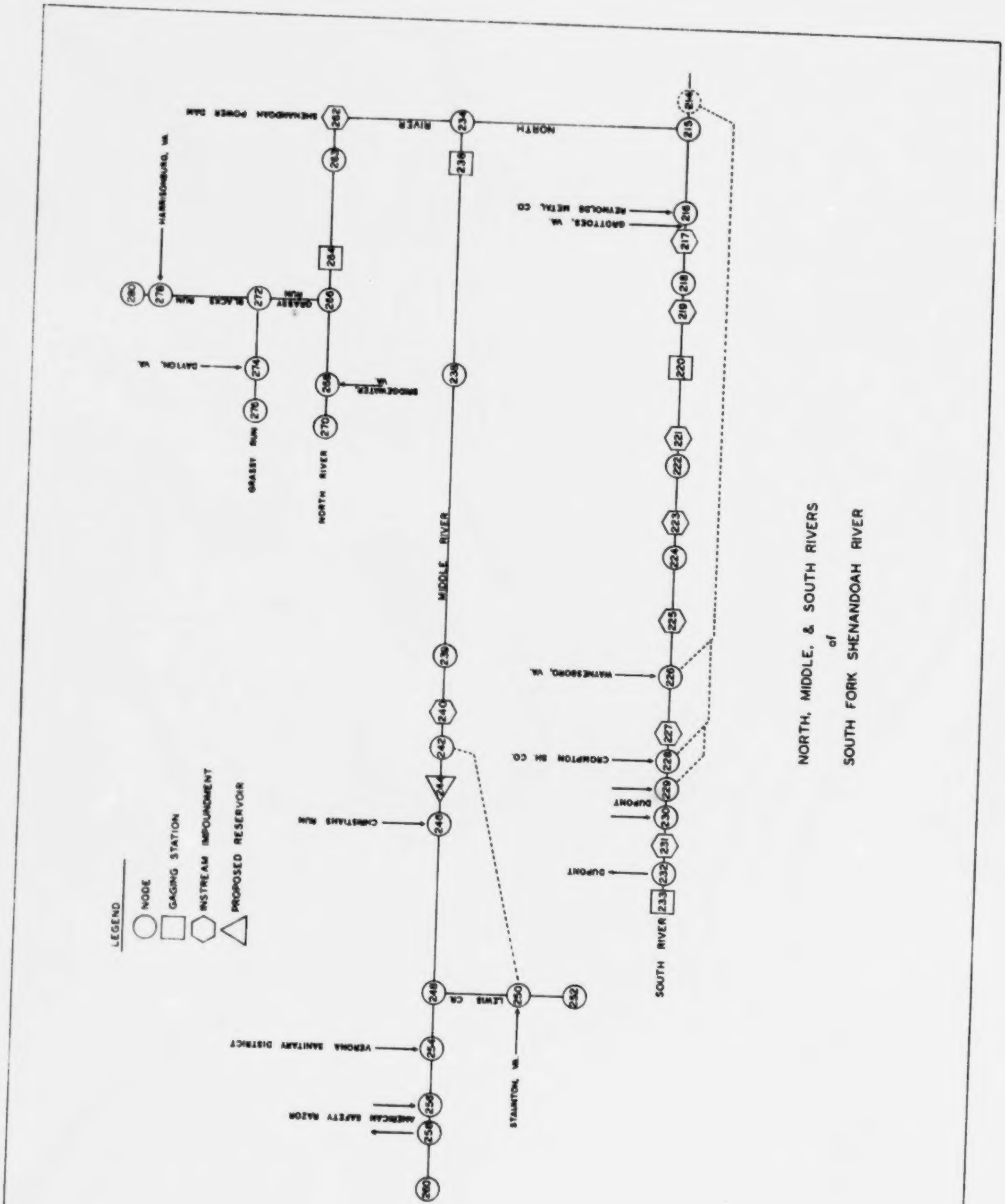

NORTH, MIDDLE, & SOUTH RIVERS
of
SOUTH FORK SHENANDOAH RIVER
LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
NORTH RIVER
MIDDLE RIVER
SOUTH RIVER
NORTH RIVER
GRASSY RUN
GRASSY RUN
BLACKS RUN
LEWIS CR.
SHENANDOAH POWER DAM
HARRISONBURG, VA.
DAYTON, VA.
BRIDGEWATER, VA.
CHRISTIANS RUN
VERONA SANITARY DISTRICT
AMERICAN SAFETY RAZOR
STAUNTON, VA.
GROTTOES, VA.
REYNOLDS METAL CO.
WAYNESBORO, VA.
CROMPTON SH. CO.
DUPONT
DUPONT

Figure 25.

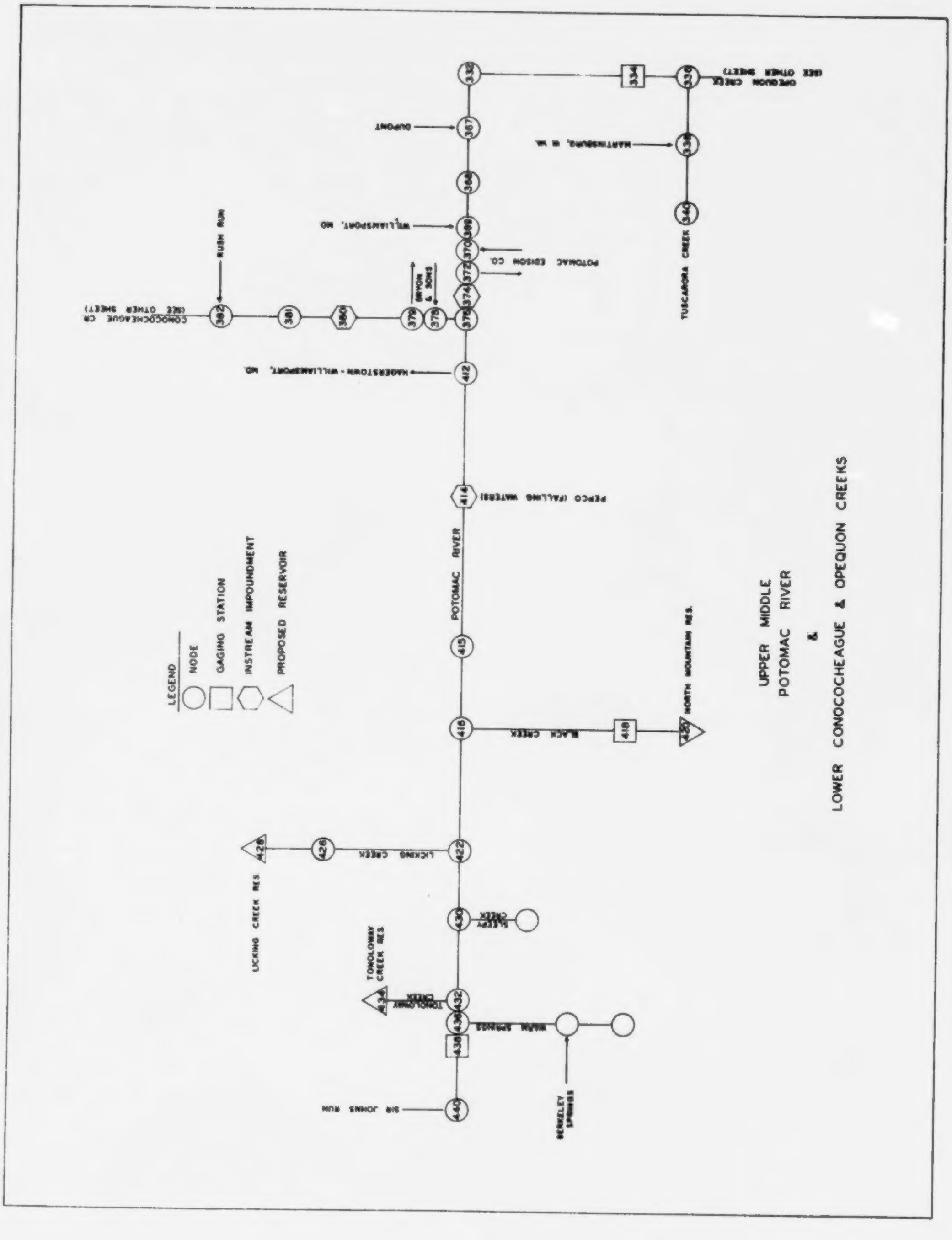
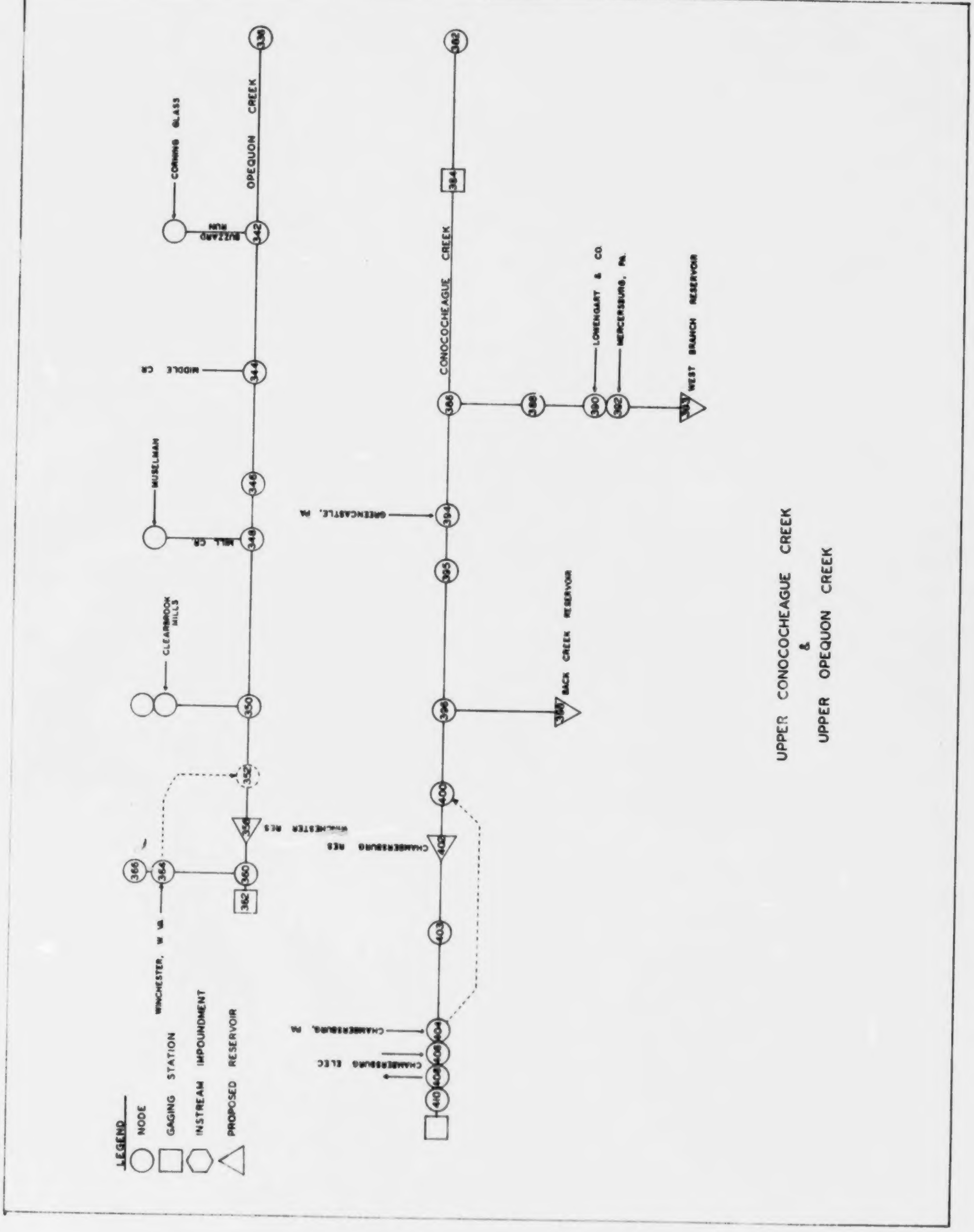
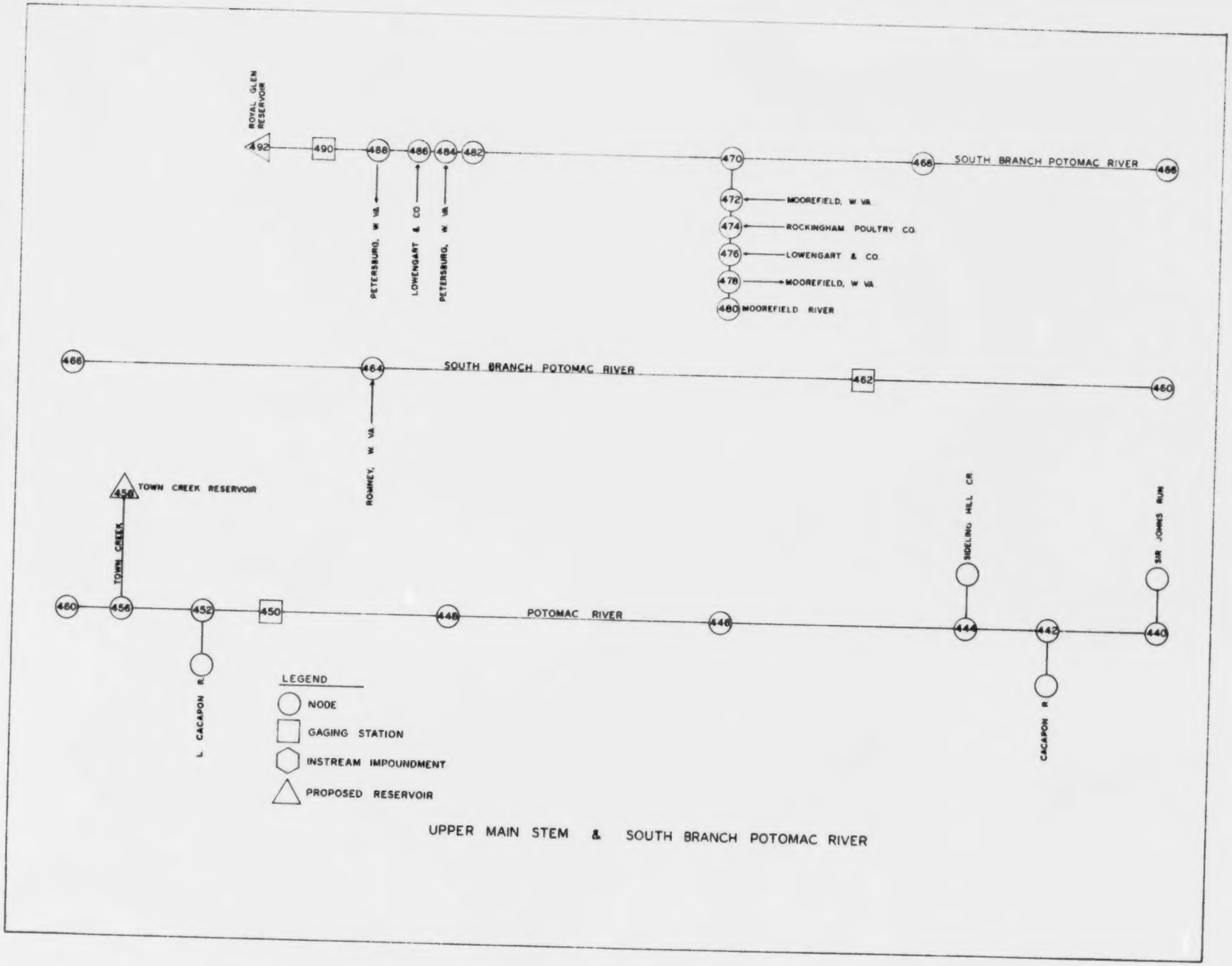

UPPER MIDDLE
POTOMAC RIVER
&
LOWER CONOCOCHEAGUE & OPEQUON CREEKS
LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
OPEQUON CREEK (SEE OTHER SHEET)
332
334
336
338
340
MARTINSBURG, W. VA.
TUSCARORA CREEK
DUPONT
367
368
369
370
372
374
376
378
379
380
381
382
WILLIAMSPORT, MD
POTOMAC EDISON CO.
BRYON & SONS
RUSH RUN
CONOCOCHEAGUE CR (SEE OTHER SHEET)
HAGERSTOWN-WILLIAMSPORT, MD.
412
414
PEPCO (FALLING WATERS)
POTOMAC RIVER
415
416
BLACK CREEK
418
420
NORTH MOUNTAIN RES.
422
LICKING CREEK
426
428
LICKING CREEK RES
430
SLEEPY CREEK
432
TONOLOWAY CREEK
434
TONOLOWAY CREEK RES
436
WARM SPRINGS
BERKELEY SPRINGS
438
440
SIR JOHNS RUN

Figure 26


LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
OPEQUON CREEK
336
CORNING GLASS
BUZZARD RUN
342
MIDDLE CR
344
346
MUSELMAN
MILL CR.
348
CLEARBROOK MILLS
350
352
WINCHESTER RES
358
360
362
364
366
WINCHESTER, W VA
CONOCOCHEAGUE CREEK
382
384
386
388
390
392
LOWENGART & CO.
MERCERSBURG, PA.
WEST BRANCH RESERVOIR
GREENCASTLE, PA
394
395
396
BACK CREEK RESERVOIR
400
402
CHAMBERSBURG RES
403
404
406
408
410
CHAMBERSBURG, PA
CHAMBERSBURG ELEC

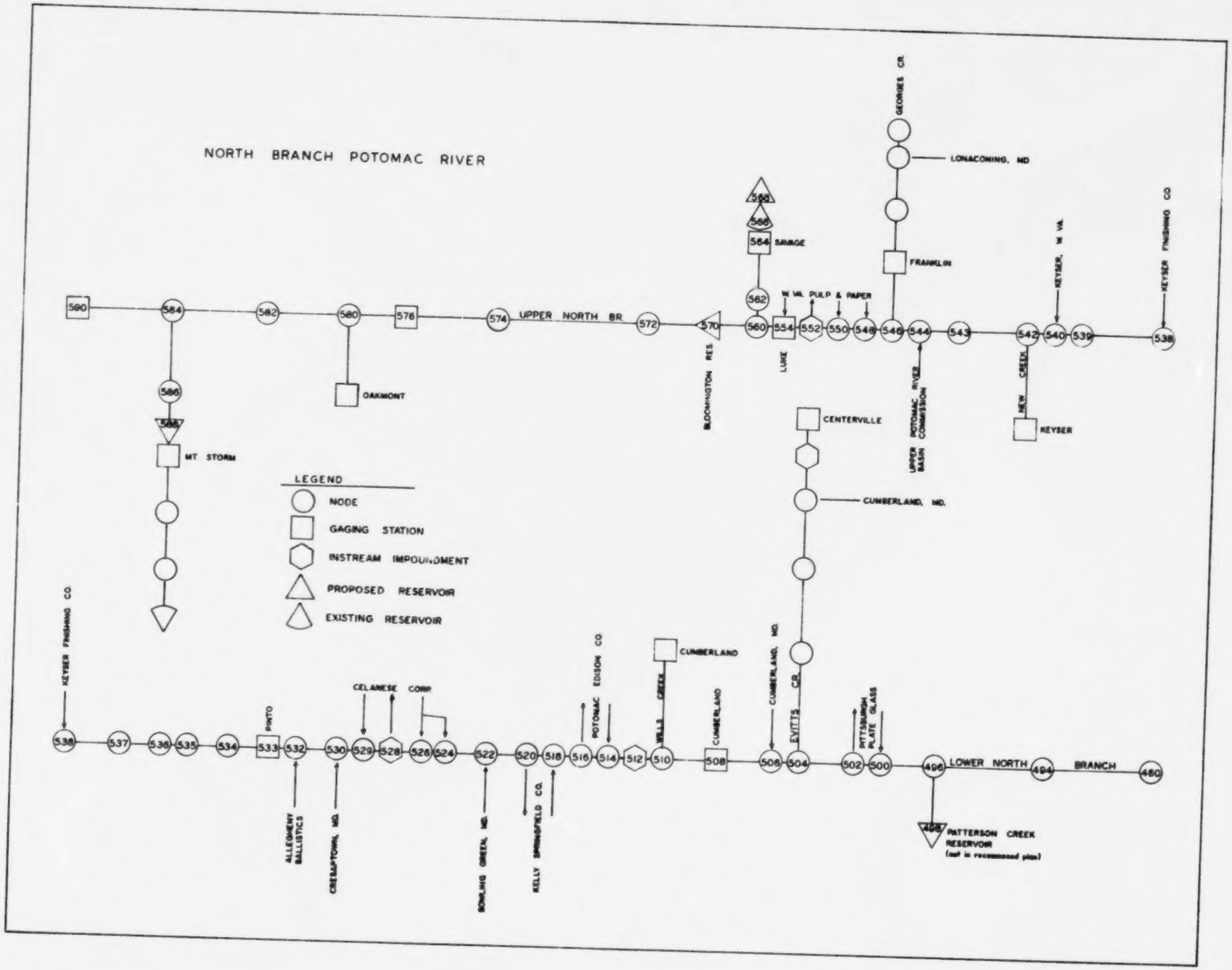
UPPER CONOCOCHEAGUE CREEK
&
UPPER OPEQUON CREEK

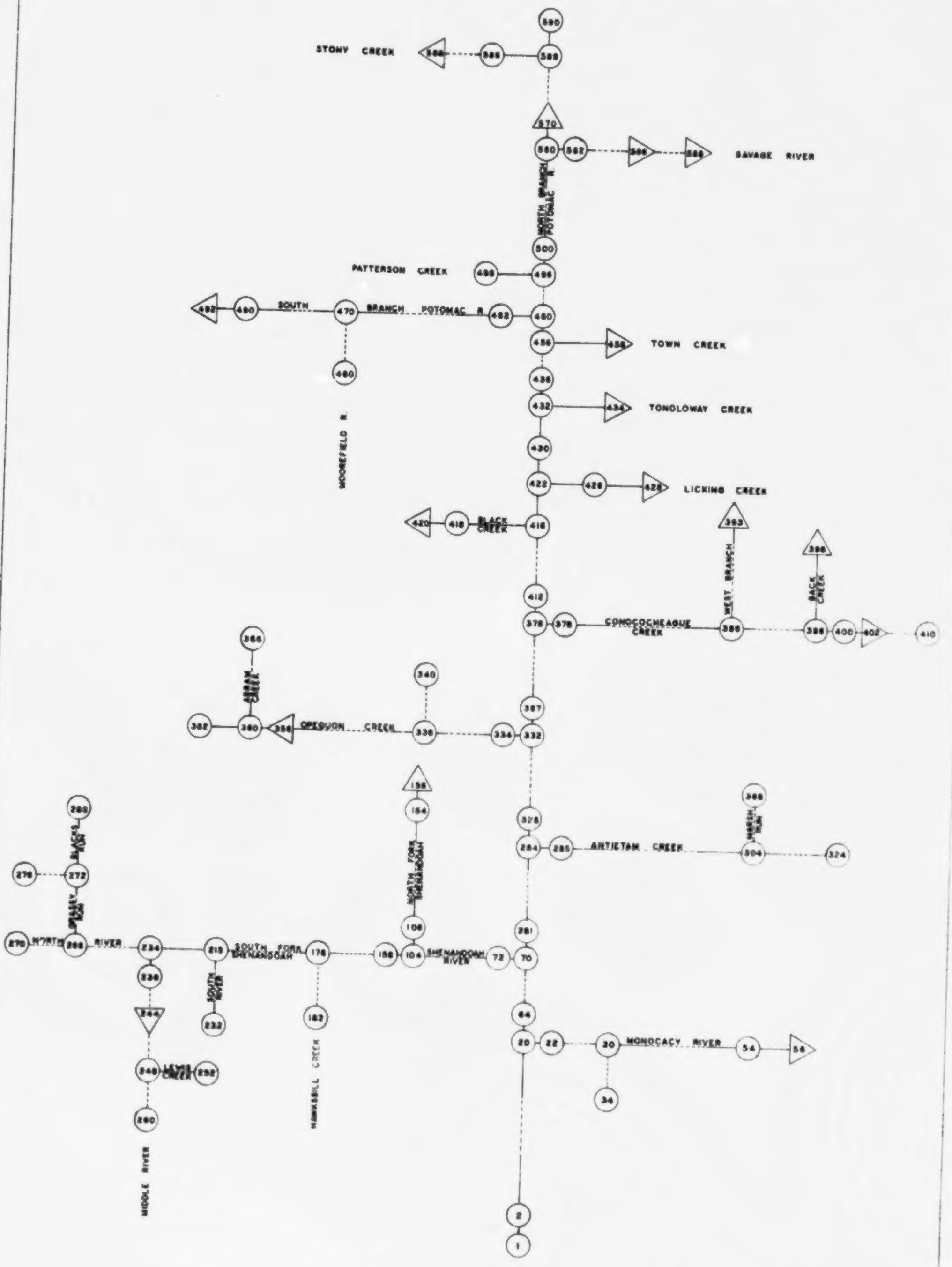
Figure 27


ROYAL GLEN RESERVOIR
492
490
488
486
484
482
PETERSBURG, W VA
LOWENGART & CO
PETERSBURG, W VA
470
468
SOUTH BRANCH POTOMAC RIVER
466
472
MOOREFIELD, W VA
474
ROCKINGHAM POULTRY CO.
476
LOWENGART & CO.
478
MOOREFIELD, W VA
480
MOOREFIELD RIVER
466
464
SOUTH BRANCH POTOMAC RIVER
462
460
ROMNEY, W VA
458
TOWN CREEK RESERVOIR
TOWN CREEK
460
456
452
450
448
POTOMAC RIVER
446
444
442
440
L. CACAPON R.
SIDELING HILL CR
CACAPON R
SIR JOHNS RUN
LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR

UPPER MAIN STEM & SOUTH BRANCH POTOMAC RIVER

Figure 28


NORTH BRANCH POTOMAC RIVER
LEGEND
NODE
GAGING STATION
INSTREAM IMPOUNDMENT
PROPOSED RESERVOIR
EXISTING RESERVOIR
590
584
582
580
576
574
UPPER NORTH BR
572
570
BLOOMINGTON RES
560
554
LUKE
552
550
548
546
544
543
542
540
539
538
562
564
SAVAGE
566
568
W. VA. PULP & PAPER
GEORGES CR.
LONACONING, MD
FRANKLIN
UPPER POTOMAC RIVER BASIN COMMISSION
NEW CREEK
KEYSER
KEYSER, W. VA.
KEYSER FINISHING CO
586
588
MT STORM
OAKMONT
CENTERVILLE
CUMBERLAND, MD.
538
KEYSER FINISHING CO.
537
536
535
534
533
PINTO
532
ALLEGHENY BALLISTICS
530
CRESAPTOWN, MD.
529
528
526
524
CELANESE CORP
522
BOWLING GREEN, MD.
520
518
KELLY SPRINGFIELD CO.
516
514
POTOMAC EDISON CO
512
510
WILLS CREEK
CUMBERLAND
508
CUMBERLAND
506
CUMBERLAND, MD.
504
EVITTS CR.
502
500
PITTSBURGH PLATE GLASS
496
LOWER NORTH
494
BRANCH
480
498
PATTERSON CREEK RESERVOIR
(not in recommend plan)


590
589
585
STONY CREEK
570
560
562
566
568
SAVAGE RIVER
NORTH BRANCH POTOMAC R.
500
PATTERSON CREEK
498
496
492
490
SOUTH
470
BRANCH POTOMAC R.
462
460
480
MOOREFIELD R.
456
458
TOWN CREEK
436
432
434
TONOLOWAY CREEK
430
422
426
428
LICKING CREEK
420
418
BLACK CREEK
416
393
WEST BRANCH
396
BACK CREEK
412
376
378
CONOCOCHEAGUE CREEK
386
398
400
402
410
366
ABRAM CREEK
362
360
356
OPEQUON CREEK
340
336
334
332
387
156
154
NORTH FORK SHENANDOAH
106
328
284
285
ANTIETAM CREEK
368
MARSH RUN
304
324
290
BLACKS RUN
276
272
270
NORTH
266
RIVER
234
236
244
248
LEWIS CREEK
252
260
MIDDLE RIVER
215
SOUTH FORK SHENANDOAH
SOUTH RIVER
232
176
182
HAWKSBILL CREEK
158
104
SHENANDOAH RIVER
72
70
281
64
20
22
30
MONOCACY RIVER
54
56
34
2
1

OVERALL POTOMAC RIVER BASIN SYSTEM

Figure 30

Table 16

STREAM FLOW DATA FOR FLOW RELEASE MODEL

Potomac River Basin

Number	Node	Index	Drainage Area (sq mi.)	Base Flow*** (cfs)	Stream	Tributary To
1	6	0	100	5	Difficult Run	Potomac River
2	14	0	460	10	Seneca Creek	Potomac River
3	16	0	400	2	Goose Creek	Potomac River
4	22	0	80	5	Bennett Creek	Monocacy River
5	26	0	70	4	Add Point	Monocacy River
6	34	1	100	10	Linganore Creek	Monocacy River
7	38	0	30	3	Carroll Creek	Monocacy River
8	44	0	25	3	Israel Creek	Monocacy River
9	48	0	65	4	Fishing Creek	Monocacy River
10	50	0	35	2	Hunting Creek	Monocacy River
11	52	0	65	3	Owens Creek	Monocacy River
12	54	0	192	15	Double Pipe Creek	Monocacy River
13	56	2	308	10	Six Bridge Reservoir*	Monocacy River
14	68	0	350	4	Catoctin Creek	Potomac River
15	82	0	54	7	Evitts Run	Shenandoah River
16	88	0	100	12	Dry Run	Shenandoah River
17	92	0	100	12	Add Point	Shenandoah River
18	96	0	111	12	Manassas Creek	Shenandoah River
19	110	0	146	12	Passage Creek	N. Fk. Shenandoah
20	112	0	118	10	Cedar Creek	N. Fk. Shenandoah
21	120	0	123	11	Add Point	N. Fk. Shenandoah
22	132	0	140	11	Stony Creek	N. Fk. Shenandoah
23	134	0	109	10	Mill Creek	N. Fk. Shenandoah
24	138	0	130	11	Smiths Creek	N. Fk. Shenandoah
25	148	0	57	19	Linville Creek	N. Fk. Shenandoah
26	156	2	213	4	Brocks Gap Reservoir*	N. Fk. Shenandoah

TABLE 16 (Continued)

Number	Node	Index	Drainage Area (sq. mi.)	Base Flow*** (cfs)	Stream	Tributary To
27	168	0	43	6	Add Point	S. Fk. Shenandoah
28	172	0	132	20	Add Point	S. Fk. Shenandoah
29	182	1	78	13	Hawkbill Creek	S. Fk. Shenandoah
30	194	0	100	17	Add Point	S. Fk. Shenandoah
31	200	0	115	17	Add Point	S. Fk. Shenandoah
32	210	0	135	23	Add Point	S. Fk. Shenandoah
33	220	0	70	13	Add Point	S.R.S. Fk. Shenandoah
34	224	0	64	11	Add Point	S.R.S. Fk. Shenandoah
35	233	1	136	26	South River	S. Fk. Shenandoah
36	239	0	45	9	Add Point	M.R.S. Fk. Shenandoah
37	244	2	325	50	Middle River*	S. Fk. Shenandoah
38	270	1	380	38	North River	S. Fk. Shenandoah
39	276	1	20	2	Grassy Run	N.R.S. Fk. Shenandoah
40	280	1	20	2	Blacks Run	N.R.S. Fk. Shenandoah
41	286	0	68	17	Add Point	Antietam Creek
42	287	0	70	17	Add Point	Antietam Creek
43	308	1	32	8	Add Point	Antietam Creek
44	316	0	35	18	Little Antietam	Antietam Creek
45	320	0	40	12	West Branch	Antietam Creek
46	324	1	50	12	Add Point	Antietam Creek
47	330	0	68	5	Add Point	Potomac River
48	334	0	73	7	Add Point	Opequon Creek
49	340	1	22	2	Tuscarora Creek	Opequon Creek
50	342	0	50	6	Add Point	Opequon Creek
51	348	0	50	6	Mill Creek	Opequon Creek
52	350	0	39	4	Add Point	Opequon Creek
53	356	2	111	10	Winchester Reservoir*	Opequon Creek
54	382	0	69	9	Add Point	Conococheague Creek
55	388	0	100	10	Add Point	W. Br. Conococheague

Table 16 (Continued)

Number	Node	Index	Drainage Area (sq mi)	Base Flow*** (cfs)	Stream	Tributary To
56	393	2	134	16	West Branch Reservoir	Conococheague Creek
57	395	0	38	4	Add Point	Conococheague Creek
58	398	2	80	8	Back Creek Reservoir*	Conococheague Creek
59	402	2	142	16	Chambers Reservoir	Conococheague Creek
60	428	2	273	5	North Mt. Reservoir*	Black Creek
61	428	2	214	7	Licking Creek Reservoir*	Licking Creek
62	430	0	273	6	Sleepy Creek	Potomac River
63	434	2	127	4	Tonoloway Creek Reservoir	Potomac River
64	440	0	90	4	Sir Johns Run	Potomac River
65	442	0	683	41	Cacapon Run	Potomac River
66	444	0	100	4	Sideling Hill Creek	Potomac River
67	446	0	91	4	Add Point	Potomac River
68	452	0	108	4	Little Cacapon River	Potomac River
69	458	2	180	5	Town Creek Reservoir*	Potomac River
70	462	0	93	6	South Bridge	Potomac River
71	466	0	200	11	Add Point	S. Br. Potomac River
72	480	1	300	10	Moorefield River	S. Br. Potomac River
73	482	0	260	13	Add Point	S. Br. Potomac River
74	492	2	640	40	Royal Glen Reservoir*	S. Br. Potomac River
75	498	1	278	5	Patterson Creek	N. Br. Potomac River
76	504	0	175	2	Evitts Creek	N. Br. Potomac River
77	510	0	275	14	Wills Creek	N. Br. Potomac River
78	542	0	120	2	New Creek	N. Br. Potomac River
79	546	0	80	3	Georges Creek	N. Br. Potomac River
80	566	2	112	62	Savage River and **	N. Br. Potomac River
81	570	2	288	32	Bloomington Reservoir*	N. Br. Potomac River

* Denotes proposed reservoirs

** Regulated by Savage I Reservoir

*** Minimum 7-day low flow with a recurrence interval of once in 10 years

Table 17

SURFACE WATER SUPPLY & WASTE WATER INVENTORY

Potomac River Basin

Name	Type	Node	Flow (cfs)	Receiving Stream
District of Columbia	2	2	2.20	Potomac River
District of Columbia	5	10	167.00	Potomac River
Washington Suburban Sanitary Commission	5	11	5.50	Potomac River
Rockville, Maryland	5	12	2.20	Potomac River
Potomac Electric and Power Company	3	17	355.00	Potomac River
Potomac Electric and Power Company	5	18	355.00	Potomac River
Frederick, Maryland	5	32	1.10	Monocacy River
Frederick, Maryland	2	36	3.80	Monocacy River
Camp Detrick, Maryland	2	40	0.65	Monocacy River
Camp Detrick, Maryland	5	42	0.80	Monocacy River
U. S. Steel Company	5	72	0.72	Shenandoah River
U. S. Steel Company	3	74	0.72	Shenandoah River
Halltown Board Company	2	76	1.00	Shenandoah River
Potomac Edison Company	3	100	10.64	Shenandoah River
Potomac Edison Company	5	102	10.64	Shenandoah River
Winchester, Virginia	5	108	2.80	N. Fk. Shenandoah River
Strasburg, Virginia	2	116	0.30	N. Fk. Shenandoah River
Woodstock, Virginia	2	126	0.14	N. Fk. Shenandoah River
Mt. Jackson, Virginia	2	136	0.11	N. Fk. Shenandoah River
New Market, Virginia	2	140	0.35	N. Fk. Shenandoah River
Shen. Valley Packers	2	142	0.18	N. Fk. Shenandoah River
Rockingham Poultry	2	144	0.71	N. Fk. Shenandoah River
Timberville, Virginia	5	146	1.00	N. Fk. Shenandoah River
Broadway, Virginia	2	150	0.13	N. Fk. Shenandoah River
Broadway, Virginia	5	152	0.10	N. Fk. Shenandoah River
Front Royal, Virginia	2	158	0.85	S. Fk. Shenandoah River
American Viscose Company	2	160	13.45	S. Fk. Shenandoah River
Old Virginia, Inc.	2	162	0.10	S. Fk. Shenandoah River
American Viscose Company	5	164	13.50	S. Fk. Shenandoah River
Virginia Oak Tannery	2	178	0.28	S. Fk. Shenandoah River
Luray, Virginia	2	180	0.28	S. Fk. Shenandoah River
Shenandoah, Virginia	2	198	0.71	S. Fk. Shenandoah River
Shenandoah, Virginia	5	202	0.50	S. Fk. Shenandoah River
Elkton, Virginia	2	204	0.18	S. Fk. Shenandoah River
Merck and Company	2	205	7.86	S. Fk. Shenandoah River
Grottoes, Virginia	2	216	0.09	S.R.S. Fk. Shenandoah
Reynolds Metal Company	2	216	2.33	S.R.S. Fk. Shenandoah
Waynesboro, Virginia	2	226	2.50	S.R.S. Fk. Shenandoah
Crompton-Shenandoah Company	2	228	2.21	S.R.S. Fk. Shenandoah
E. I. Dupont Company	2	229	10.80	S.R.S. Fk. Shenandoah
E. I. Dupont Company	3	230	16.27	S.R.S. Fk. Shenandoah

Table 17 (Continued)

Name	Type	Node	Flow (cfs)	Receiving Stream
E. I. Dupont Company	5	232	14.40	S.R.S. Fk. Shenandoah
Staunton, Virginia	2	250	3.30	M.R.S. Fk. Shenandoah
Verona Sanitary District, Virginia	2	254	0.19	M.R.S. Fk. Shenandoah
American Safety Razor Company	2	256	0.50	M.R.S. Fk. Shenandoah
American Safety Razor Company	5	258	0.50	M.R.S. Fk. Shenandoah
Bridgewater, Virginia	2	268	0.26	N.R.S. Fk. Shenandoah
Dayton, Virginia	2	274	0.16	N.R.S. Fk. Shenandoah
Harrisonburg, Virginia	2	278	2.25	N.R.S. Fk. Shenandoah
Hagerstown, Maryland	2	296	5.75	Antietam Creek
Hagerstown Electric	3	298	0.33	Antietam Creek
Hagerstown Electric	5	302	0.33	Antietam Creek
Fairchild Aircraft Company	2	306	0.50	Antietam Creek
North American Cement Company	3	310	7.83	Antietam Creek
North American Cement Company	5	312	8.12	Antietam Creek
Waynesboro, Pennsylvania	2	322	1.20	Antietam Creek
Shepherdstown, West Virginia	2	326	0.14	Potomac River
Martinsburg, West Virginia	2	338	2.00	Opequon Creek
Minnesota M & M Company	2	346	0.45	Opequon Creek
Winchester, West Virginia	2	364	2.53	Opequon Creek
E. I. Dupont Company	2	367	0.40	Potomac River
Williamsport, Maryland	2	369	0.19	Potomac River
Potomac Edison Company	3	370	72.42	Potomac River
Potomac Edison Company	5	372	72.42	Potomac River
Byron and Sons Company	2	378	0.30	Conococheague Creek
Byron and Sons Company	5	380	0.21	Conococheague Creek
Lowengart and Company	2	390	0.12	W. Br. Conococheague
Mercersburg, Pennsylvania	2	392	0.22	W. Br. Conococheague
Greencastle, Pennsylvania	2	394	0.13	Conococheague Creek
Chambersburg, Pennsylvania	2	404	3.00	Conococheague Creek
Chambersburg Electric	3	406	2.50	Conococheague Creek
Chambersburg Electric	5	408	2.50	Conococheague Creek
Williamsport, Maryland	5	412	6.73	Potomac River
Romney, West Virginia	2	464	0.30	S. Br. Potomac River
Moorefield, West Virginia	2	472	0.17	S. Br. Potomac River
Rockingham Poultry Company	2	474	0.15	S. Br. Potomac River
Lowengart and Company	2	476	0.13	S. Br. Potomac River
Moorefield, West Virginia	5	478	0.25	S. Br. Potomac River
Petersburg, West Virginia	2	484	0.34	S. Br. Potomac River
Lowengart and Company	2	486	0.20	S. Br. Potomac River
Petersburg, West Virginia	5	488	2.00	S. Br. Potomac River

Table 17 (Continued)

Name	Type	Node	Flow (cfs)	Receiving Stream
Pittsburgh Plate Glass	2	500	2.00	N. Br. Potomac River
Pittsburgh Plate Glass	2	502	0.26	N. Br. Potomac River
Cumberland, Maryland	2	506	5.00	N. Br. Potomac River
Potomac Edison Company	3	514	0.69	N. Br. Potomac River
Potomac Edison Company	5	516	0.67	N. Br. Potomac River
Kelly Springfield Company	3	518	3.60	N. Br. Potomac River
Kelly Springfield Company	5	520	2.93	N. Br. Potomac River
Bowling Green, Maryland	2	522	0.18	N. Br. Potomac River
Celanese Corporation	2	524	2.80	N. Br. Potomac River
Celanese Corporation	3	526	58.00	N. Br. Potomac River
Celanese Corporation	5	528	58.00	N. Br. Potomac River
Celanese Corporation	2	529	2.60	N. Br. Potomac River
Cresaptown, Maryland	2	530	0.28	N. Br. Potomac River
Allegheny Ballistics	2	532	0.27	N. Br. Potomac River
Keyser Finishing Company	2	538	0.25	N. Br. Potomac River
Keyser, West Virginia	2	540	2.00	N. Br. Potomac River
Upper Potomac River Basin Commission	2	544	[illegible]	N. Br. Potomac River
West Virginia Pulp and Paper Company	2	548	7.50	N. Br. Potomac River
West Virginia Pulp and Paper Company	3	550	29.00	N. Br. Potomac River
West Virginia Pulp and Paper Company	[illegible]	552	23.50	N. Br. Potomac River
West Virginia Pulp and Paper Company	[illegible]	554	13.00	N. Br. Potomac River

COST OF DATA

As indicated in Appendix A, a large amount of field work including stream and waste treatment surveys is required to implement the flow release model. In order to determine the cost of collecting the necessary information required to implement the model, cost figures have been kept on some of the major field activities at the Chesapeake Field Station.

A summary of the cost data is given in Table 18.

Table 18

COST OF FIELD STUDIES

Activity	Unit of Measurement	Cost Range/Unit
Time of travel	per mile	$ 50 - $ 100
Cross-sectioning	per section	$ 4 - $ 10
Waste Treatment Plant Survey	per 24-hour survey	$2000 - $3000
Stream Survey	per sample	$ 25 - $ 50

The above cost figures include personnel time plus a 33 percent overhead charge. The waste treatment plant and stream survey consists of routine sanitary analyses such as BOD, DO, solids, and nutrients. The large cost range reflects the additional expense of per diem and overtime when the activities are in remote areas of the basin.

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APPENDIX C

COMPUTER PROGRAM DOCUMENTATION AND USAGE WITH SAMPLE PROBLEM

GENERAL

The computer programs for the verification link and flow release model have been coded in FORTRAN IV Subset E. The same algorithms, notations and data inputs are common to both programs.

For easy reading and understanding of the programs, symbols for the variables are usually abbreviations of the algorithm parameters. Allowances have been made for possible expansion of the model concepts, including input formats.

In the verification link, all calculations are made in the concentration mode (mg/1), while in the flow release model, the mode is pounds/day. The use of concentration in the verification link aids in displaying of the various profiles. For example, the computed BOD profile is listed as 5-day BOD values, which simplifies comparison to field data.

DATA FORMATS AND TYPICAL DECK COMPUTATIONS

Detailed listings of the ten-input formats and array notation are presented in Tables 19 and 20, respectively. As can be seen in Figure 31, all input formats are fixed fields. Card format 6, which currently is optional, has been designed for possible expansion of the BOD, DO and temperature formulations and to allow for greater flexibility in the [illegible] algorithms.

Typical data deck compilations for the verification link and flow release model are displayed in Figures 32 and 33, respectively. For a [illegible] compilation, the order of compilation is as follows:

1. all levels of waste treatment for given flow module;
2. all flow sets for a given waste water module; and,

3. all waste water sets for a typical computation.

If many waste water sets are included for compilation, each waste module must contain same number of flow sets.

Since there are no data sorting routines designed into program, all formats must be placed in proper sequence. Consequently, Format 5, which is used to link the various modes, must be ranked upward by J(N) parameter.

PROGRAM USAGE WITH SAMPLE PROBLEM

To illustrate the data inputs and computer outputs formed for the verification link and flow release model, a sample set of data for the Patuxent River Basin is presented in this appendix.

For demonstration purposes, regulation capability not currently existing has been introduced in the Little Patuxent River. Cost considerations are not included in the sample problem. A schematic of the Patuxent River Basin model is given in Figure 34.

In the flow release model, the distance increment, flow increment, BOD test grid, and BOD increments are read as input data, with the latter two not required in the verification link. The latter three parameters controlled the number of feasible solutions with first, the frequency and number of water quality monitoring points in the basin.

For the sample problem, a flow increment of 5 cfs has been used. In the Potomac Basin, a 20 cfs increment appeared to be adequate. To prevent computational problems, the regulation range must be a multiple of the flow increment or vice versa. This also applies to the reservoir cost data.

To allow for maximum flexibility at a decision point (or stage), the BOD increment is selected by the computer according to BOD range for the flow state under investigation. As can be seen in the Patuxent

River Basin data, if the BOD range is between 1.0 and 0.0 mg/l, an increment of 0.2 mg/l is selected; between 2.0 and 0.0 mg/l, 0.4 mg/l; between 3.0 and 0.0 mg/l, 0.6 mg/l; etc. In the Potomac Basin, as indicated earlier, the BOD range was usually about 0.5 mg/l or less.

For the temperature model the decay coefficient appears to vary mainly according to season and stream. Verification studies of Potomac and Patuxent have indicated a coefficient range of 0.2 to 0.60, with a typical value of about 0.3.

Table 19

CARD FORMATS FOR VERIFICATION LINK AND FLOW RELEASE MODEL

Main Parameter Card (No. 1)

Symbol	Description	Field
TOTALN	Number of stream sections	1-5
TOTALW	Number of water intakes and waste water discharge	6-10
TOTALP	Number of streamflow add points	11-15
NRES	Number of reservoirs	16-20
FIRST1	First node of basin or terminal node of data sets	21-25
ITO	Number of data sets	26-30
TFL	Number of flow sets per data set	31-35
IRMBOD	Number of treatment levels per data set	36-40
ITBOD	Index for waste water BOD loading 1. in pounds/day 2. in mg/l	41-45
OPTYPE	Index for optimization 1. BOD-DOD routine 2. BOD-COST routine	46-50
IRCIT	Index for reaeration formulation 1. O'Connor 2. Churchill 3. U.S.G.S.	51-55
DELTA	Flow increment from reservoirs in cfs	56-60
REMBOD	Minimum BOD removal level of all waste waters	61-65
RM(FIRST)	River mileage of first node	66-70
INC	Distance increment of BOD-DO quality formulations in miles	71-75
REMPHS	Minimum phosphorus removal level of all waste waters	76-80

Table 19 (Continued)

Five Waste Treatment Levels (No 2)

Symbol	Description	Field
WSTP(1)	First minimal BOD removal level of all waste waters	1-10
WSTP(2)	Second minimal BOD removal level of all waste waters	11-20
WSTP(3)	Third minimal BOD removal level of all waste waters	21-30
WSTP(4)	Fourth minimal BOD removal level of all waste waters	31-40
WSTP(5)	Fifth minimal BOD removal level of all waste waters	41-50

Dynamic Programming Data - Grid Increment (No. 3)

Symbol	Description	Field
ADD1	BOD grid increment for Test 1 grid	1-10
ADD2	BOD grid increment for Test 2 grid	11-20
ADD3	BOD grid increment for Test 3 grid	21-30
ADD4	BOD grid increment for Test 4 grid	31-40
ADD5	BOD grid increment for Test 5 grid	41-50

Dynamic Programming Data - Test Grid (No. 4)

Symbol	Description	Field
TEST1	First BOD test grid size	1-10
TEST2	Second BOD test grid size	11-20
TEST3	Third BOD test grid size	21-30
TEST4	Fourth BOD test grid size	31-40
TEST5	Fifth BOD test grid size	41-50

Table 19 (Continued)

Physical Data of Stream by Section (No. 5)

Symbol	Description	Field
II(N)	Lower node of section	1-5
JJ(N)	Upper node of section	6-10
TDIS(N)	River mile distance at upper node	11-20
DAREA(N)	Drainage of basin at upper node	21-30
AA(N)	Constant of depth-flow relationship for section	31-40
BB(N)	Exponent of depth-flow relationship for section	41-50
CC(N)	Constant of velocity-flow relationship for section	51-60
DD(N)	Exponent of velocity-flow relationship for section	61-70
NNTYPE(N)	Index of upper node 1. Node where there is a physical discontinuity 2. Confluence of two tributaries 3. Waste water discharge 4. Water intake 5. Cooling water discharge 6. Regulated terminal stream flow source 7. Unregulated terminal stream flow source	71-75

Table 19 (Continued)

Continuation of Card 5 - Optional (No. 6)

Symbol	Description	Field
II(N)	Lower node of section	1-5
JJ(N)	Upper node of section	6-10
SLOPE(N)	Slope of section (ft/ft)	11-20
DPFAC(N)	Depth factor of section	21-25
CONST(N)	DO constraint of section	26-30
DECAYT(N)	Temperature decay coefficient of section	31-35
TTEMP(N)	Steady-state temperature of section	36-40
DECAYP(N)	Phosphorus decay coefficient of section	41-45
PPHOS(N)	Dynamic-equilibrium level of phosphorus	46-50
PHOTOS(N)	Photosynthesis DO contribution (future use)	51-55
SLDGE(N)	BOD contribution of sludge deposits (future use)	56-60
EXTBOD(N)	BOD loss due to extraction (future use)	61-65
SEDBOD(N)	Dynamic-equilibrium level of BOD	66-70

Table 19 (Continued)

Reservoir Information (No. 7)

Symbol	Description	Field
NRES(N)	Reservoir Number	1-5
NRN(N)	Node of reservoir	6-10
MRES(N)	Number of cost cards	11-15
IRES(N)	Flow increment for cost increment	16-20
ACREFT(N)	Total storage of reservoir in acre-feet	21-30
WQ ACFT(N)	Total storage for water quality control in acre-feet	31-40
TCOST(N)	Total cost of reservoir	41-50
WQ COST(N)	Cost of storage for water quality control	51-60
AVRESQ(N)	Average stream flow at reservoir	61-70
INRESQ(N)	Increase in dependable flow by reservoir	71-80

Reservoir Cost (No. 8)

Symbol	Description	Field
NRES(N)	Reservoir number	1-4
CARD	Number of cost card	5-8
COST	Reservoir cost for given flow increments (fields of six)	9-80

Table 19 (Continued)

Waste Water Discharge Data (No. 9)
(Including water intakes)

Symbol	Description	Field
WJ(N)	Node of discharge or intake	1-4
WTYPE(N)	Index of discharge or intake 1. Biological waste water discharge in cfs 2. Biological waste water discharge in mgd 3. Thermal waste water discharge in mgd 4. Conservative waste water discharge in mgd 5. Surface water supply intake in mgd	5-10
WWFLOW(N)	Discharge or intake flow (For units see WTYPE(N) index)	11-20
WK(N)	Deaeration rate (base 10 at 20°C)	21-30
WBOD(N)	BOD loading - untreated (For units see ITBOD - Card 1)	31-40
WDO(N)	DO content of waste discharge in mg/1	41-50
WTEMP(N)	Temperature of waste discharge in °C	51-60
WPHOS(N)	Phosphorus content of waste discharge in mg/1	61-70
WREM(N)	Percent BOD removal by treatment facility	71-80

Table 19 (Continued)

Secondary Parameter Card (No. 10)

Symbol	Description	Field
IT2	Index of steady-state temperature 1. Uniform basin temperature 2. Temperature by sections from Card 6	1-5
TTEMP1	Uniform basin steady-state temperature in °C	6-10
IT3	Index of DO constraint 1. Uniform basin DO constraint 2. DO constraint by sections from Card 6	11-15
CONST1	Uniform DO constraint in mg/l	16-20
IT4	Index of depth factor 1. Uniform basin depth factor 2. Depth factor by sections from Card 6	21-25
DPFAC1	Uniform depth factor	26-30
IT5	Index of temperature decay coefficient 1. Uniform basin decay coefficient 2. Decay coefficient by sections from Card 6	31-35
DKTEMP	Uniform temperature decay coefficient	36-40
IT6	Index of phosphorus decay coefficient 1. Uniform basin decay coefficient 2. Decay coefficient by sections from Card 6	41-45
DKPHOS	Uniform phosphorus decay coefficient (base 10)	46-50
IT7	Index of dynamic-equilibrium of phosphorus 1. Uniform basin equilibrium level 2. Equilibrium level by sections from Card 6	51-55
SSPHOS	Uniform dynamic-equilibrium level of phosphorus in mg/l	56-60
IT8	Index of dynamic-equilibrium level of BOD 1. Uniform basin equilibrium level 2. Equilibrium level by sections from Card 6	61-65
BODSS	Uniform dynamic-equilibrium level of BOD in mg/l	66-70

Table 19 (Continued)

Data at Streamflow Addition Points (No. 11)

Symbol	Description	Field
RJ(N)	Node of addition point	1-4
RTYPE(N)	Index of addition point 0. Increment flow addition (not a terminal source) 1. Unregulated terminal source 2. Regulated terminal source	5-8
RMINQ(N)	Minimum flow at addition point in cfs	9-15
RMAXQ(N)	Maximum flow at addition point in cfs	16-21
RBOD(N)	BOD of addition point in mg/l	22-27
RDO(N)	DO of addition point in mg/l	28-32
RPHOS(N)	Phosphorus content of addition point in mg/l	33-38
RK(N)	Deaeration rate of BOD of addition point (base 10 at 20°C)	39-45
RTEMP(N)	Temperature of addition point	46-51
RFTEMP(N)	Slope of temperature-flow relationship	52-57
RFDO(N)	Slope of DO-flow relationship	58-63
RFBOD(N)	Slope of BOD-flow relationship	64-68
RFPHOS(N)	Slope of phosphorus-flow relationship	69-75

Table 20

ARRAY NOTATION FOR VERIFICATION LINK AND FLOW RELEASE MODEL

AA(N) = Constant for the log-log depth versus flow relationship for a given section

ACREFT(N) = Acre-feet of storage in a given reservoir

AVRESQ(N) = Average flow of stream at given reservoir site

BB(N) = Exponent for the log-log depth versus flow relationship for a given section

BOD(JJ) = BOD at node in mg/l

CC(N) = Constant for the log-log velocity versus flow relationship for a given section

CONST(N) = Dissolved oxygen constraint for a given section in mg/l

DAREA(N) = Drainage area at upper node of section in square miles

DD(N) = Exponent for the log-log velocity versus flow relationship for a given section

DECAYP(N) = Decay rate for phosphorus (base 10) for a given section

DECAYT(N) = Decay rate for temperature (base e) for a given section

DEL(T) = Difference between steady-state and computed temperatures at a given point

DEPTH(N) = Average water depth in feet for a given section

DIS(JJ) = Distance in miles of given node from confluence of basin

DISTAN(T) = Distance in miles of given point from confluence of basin

DO1(T) = Dissolved oxygen concentration at given point in mg/l

DOD(T) = Dissolved oxygen deficit at given point in mg/l

DPFAC(N) = Depth factor for given section

EXTBOD(N) = For expansion to include extraction in the BOD model (Future use)

Table 20 (Continued)

I(N) = Lower node of section

INRESQ(N) = Increase in stream flow at given reservoir site by regulation

IRES(N) = Cost-flow increment for given reservoir site

J(N) = Upper node of section

LBOD(JJ) = Pounds of BOD added or deleted at a given node in #/day

LDOD(JJ) = Pounds of dissolved oxygen deficit added or deleted at a given node in #/day

LFLOW(JJ) = Flow in cfs added or deleted at a given node

LK(JJ) = Deoxygenation coefficient (base 10)

LPHOS(JJ) = Pounds of phosphorus added or deleted at a given node

LTEMP(JJ) = Temperature in degrees centigrade

MAXM(E) = Maximum number of increment in a given incremental flow tableau

MAXRQ(JJ) = Maximum flow in cfs at a given node

MBOD(JJ) = BOD in #/day for given grid unit in the incremental flow tableau

MCOST(JJ) = Cost of regulation for a given grid unit in the incremental flow tableau

MDOD(JJ) = Dissolved oxygen deficit in #/day for a given grid unit in the incremental flow tableau

MFLOW(X) = Flow in cfs for given grid unit in incremental flow tableau

MINRQ(JJ) = Minimum flow in cfs for a given node

MJ(E) = Upper node of the section for which the incremental flow tableau is calculated

MK(JJ) = Deoxygenation coefficient in days (base 10) for given grid unit of the incremental flow tableau

MN(E) = Section for which incremental flow tableaus are calculated

Table 20 (Continued)

MNRES(N) = Number of cards which contain cost data for a given reservoir site

MTEMP(JJ) = Temperature of given grid unit in the incremental flow tableau

NBOD(JJ) = Counter-part to MBOD(JJ) in dynamic programming solution

NCOST(JJ) = Similar to MCOST(JJ)

NDOD(JJ) = Counter-part to MDOD(JJ) in dynamic programming solution

NFLOW(JJ) = Counter-part to MFLOW(JJ) in dynamic programming solution

NK(JJ) = Counter-part to MK(JJ) in dynamic programming solution

NN(JJ) = Section number for given upper node

NNTYPE(N) = Index of upper node of a given section (data input)

NRES(N) = Number of given reservoir site

NRJ(N) = Node of given reservoir site

NTEMP(N) = Steady-state temperature of a given section

NRN(JJ) = Reservoir number for a given node

NTYPE(N) = Index type of upper node (reassemble by program)

OBOD(S) = BOD in mg/l of feasible solution from dynamic programming tableau

OCOST(S) = Reservoir cost of a feasible solution in the dynamic programming tableau

ODOD(S) = DO deficit of a feasible solution in the dynamic programming tableau

OFLOW(S) = Flow in cfs of a fessible solution in the dynamic programming tableau

OK(S) = Deoxygenation coefficient of feasible solution in the dynamic programming tableau (base 10)

OTEMP(S) = Temperature in degrees centigrade of feasible solution in the dynamic programming tableau

Table 20 (Continued)

OXFLOW(S) = Flow in cfs from M-arrays of feasible solution in the dynamic programming tableau

OYFLOW(S) = Flow in cfs from N-arrays of feasible solution in the dynamic programming tableau

PHOS(T) = Phosphorus in mg/l at a given point

PHOTOS(N) = For expansion to include photosynthesis in BOD model (Future use)

PPHOS(N) = Steady-state limiting value of phosphorus for a given section

RBOD(N) = BOD in mg/l at a given stream flow addition point

RCOST(NRA,ICR) = Cost data for a given reservoir for a given release rate

RDO(N) = DO in given reservoir at a given flow

REAIR(JJ) = Average reaeration coefficient for a given section (base 10)

RFBOD(N) = Slope of BOD versus flow relationship for stream flow addition point

RFDO(N) = Slope of DO versus flow relationship for stream flow addition point

RFLOW(N) = Flow in cfs for a given node

RFPHOS(N) = Slope of phosphorus versus flow relationship at a stream flow addition point

RFTEMP(N) = Slope of temperature versus flow relationship at a stream flow addition point

RJ(N) = Node of given stream flow addition point

RK(N) = Deoxygenation coefficient in 1/days at a stream flow addition point (base 10)

RMAXQ(N) = Maximum flow rate in cfs at a given stream flow addition point

RMINQ(N) = Minimum flow rate in cfs at a given stream flow addition point

Table 20 (Continued)

RPHOS(N) = Phosphorus in mg/l at a given stream flow addition point

RTEMP(N) = Temperature in degrees centigrade at a given stream flow addition point

RTYPE(N) = Index of a stream flow addition node

SATDO(T) = Dissolved oxygen saturation concentration in mg/l for a given point

SBOD(JJ) = BOD in #/days at a given node

SDELL(JJ) = Difference between steady-state and calculated temperature at a given node

SDOD(JJ) = DO deficit in #/days at a given node

SEDBOD(N) = For expansion to include sedimentation in the model (Future use)

SFLOW(JJ) = Flow in cfs at a given node

SK(JJ) = Deaeration coefficient at a given node (base 10)

SLDBOD(N) = For expansion to include sludge deposit in the BOD model (Future use)

SLOPE(N) = Slope of stream in ft/ft for a given section

SQCOST(N) = Cost storage in given reservoir for water quality control

SSBOD(T) = BOD in #/days at a given point

SSDOD(T) = DO deficit in #/days at a given point

SSTEMP(T) = Temperature in degrees centigrade at given point

STEMP(JJ) = Temperature in degrees centigrade at given node

SXFLOW(X) = Flow in cfs for given solution in the dynamic programming routine, M-arrays

SYFLOW(Y) = Flow in cfs for a given solution in the dynamic programming routine, N-arrays

TCOST(N) = Total cost of a given reservoir

Table 20 (Continued)

TDIS(N) = Distance in miles from the confluence for given node

TEMP(T) = Steady-state temperature in degrees centigrade for a given point

TRET(N) = For expansion of reservoir site data

TTEMP(N) = Steady-state temperature in degrees centigrade for a given section

VEL(JJ) = Average velocity for section in ft/sec indexed by upper node

WBOD(N) = Untreated BOD in #/day or mg/l of a waste load for a given node

WDO(N) = DO in mg/l in the waste load for given node

WFLOW(N) = Flow in cfs for a given node

WIDTH(JJ) = Average width in feet for section indexed by upper node

WJ(N) = Node of waste water discharge

WK(N) = Deaeration coefficient of waste load in 1/days (base 10)

WPHOS(N) = Phosphorus in mg/l in waste load for given node

WQACFT(Y) = Reservoir storage in acre-feet for water quality control

WREM(N) = Percent removal of BOD of given waste load

WSTP(IRM) = Minimum BOD treatment level

WTEMP(N) = Temperature in degrees centigrade of waste load for given node

WTYPE(N) = Index of waste load for a given node

WWFLOW(N) = Flow in mgd of waste load for a given node

FORMATS FOR DATA CARDS

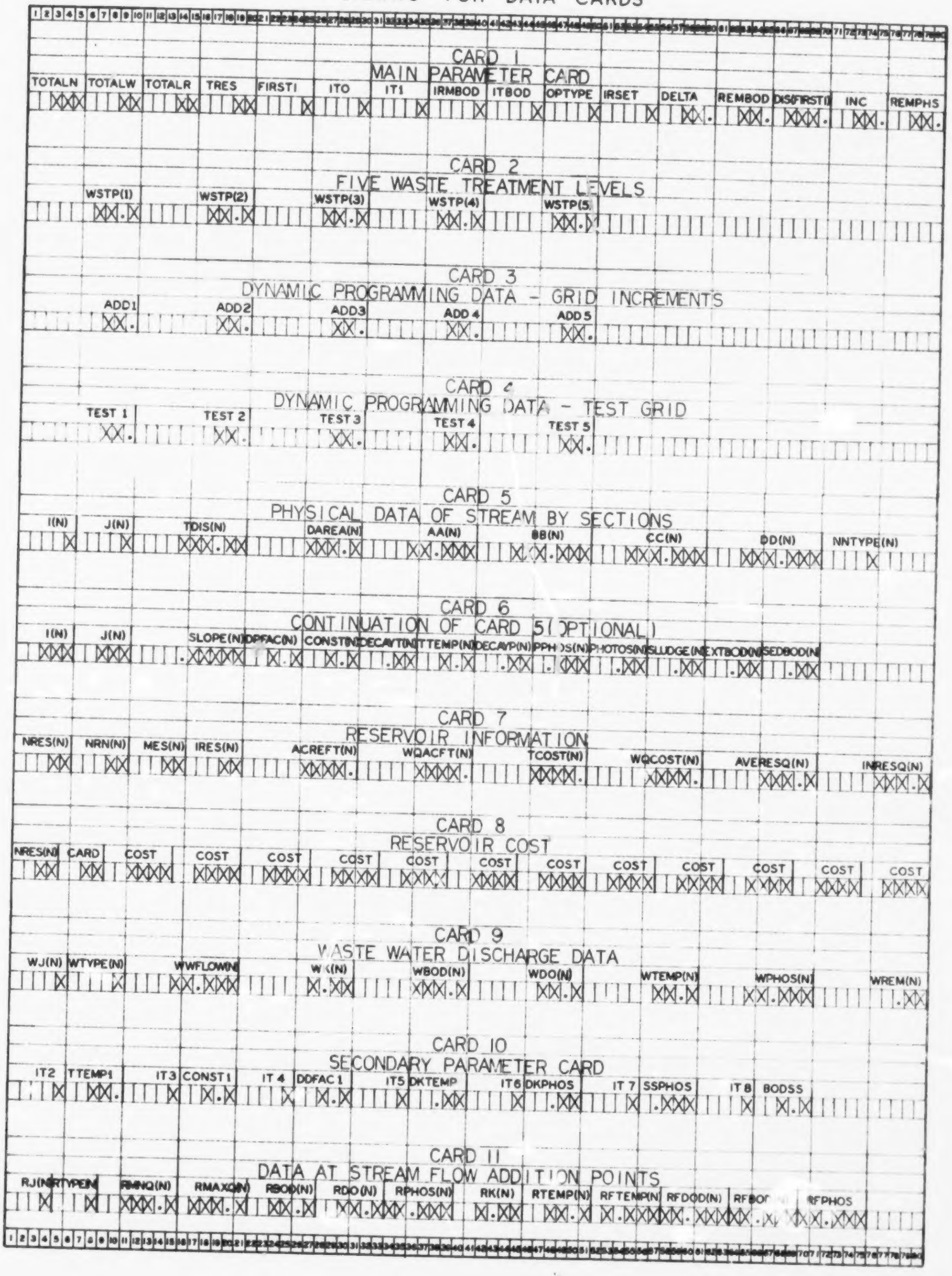
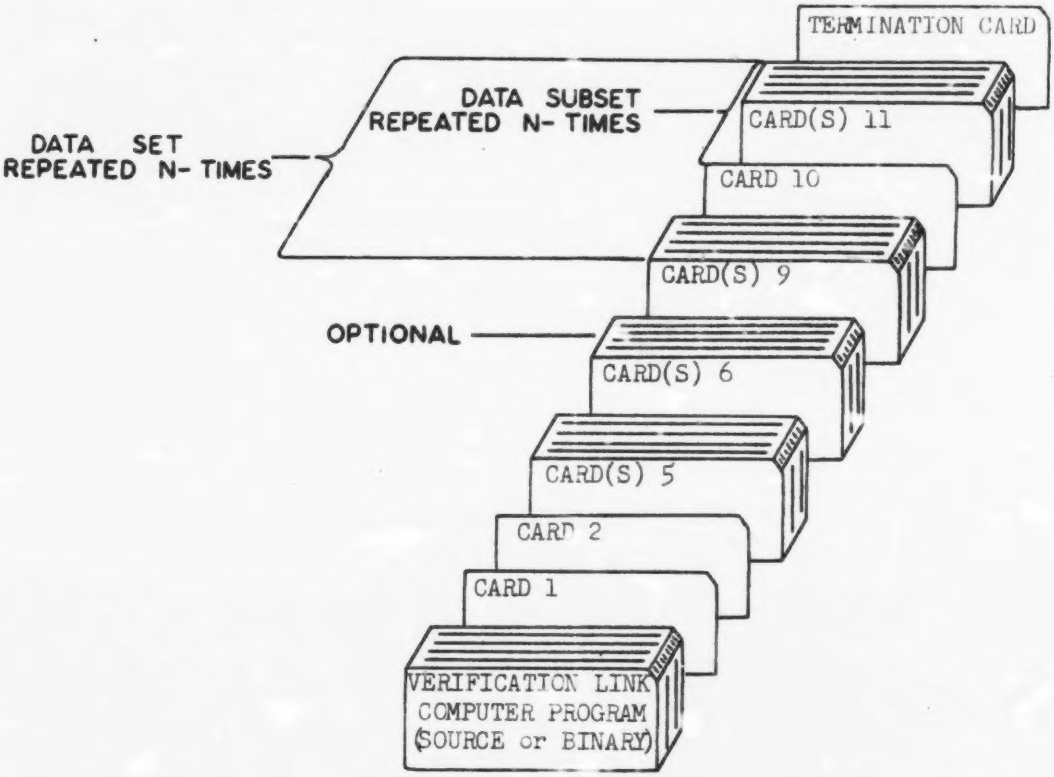
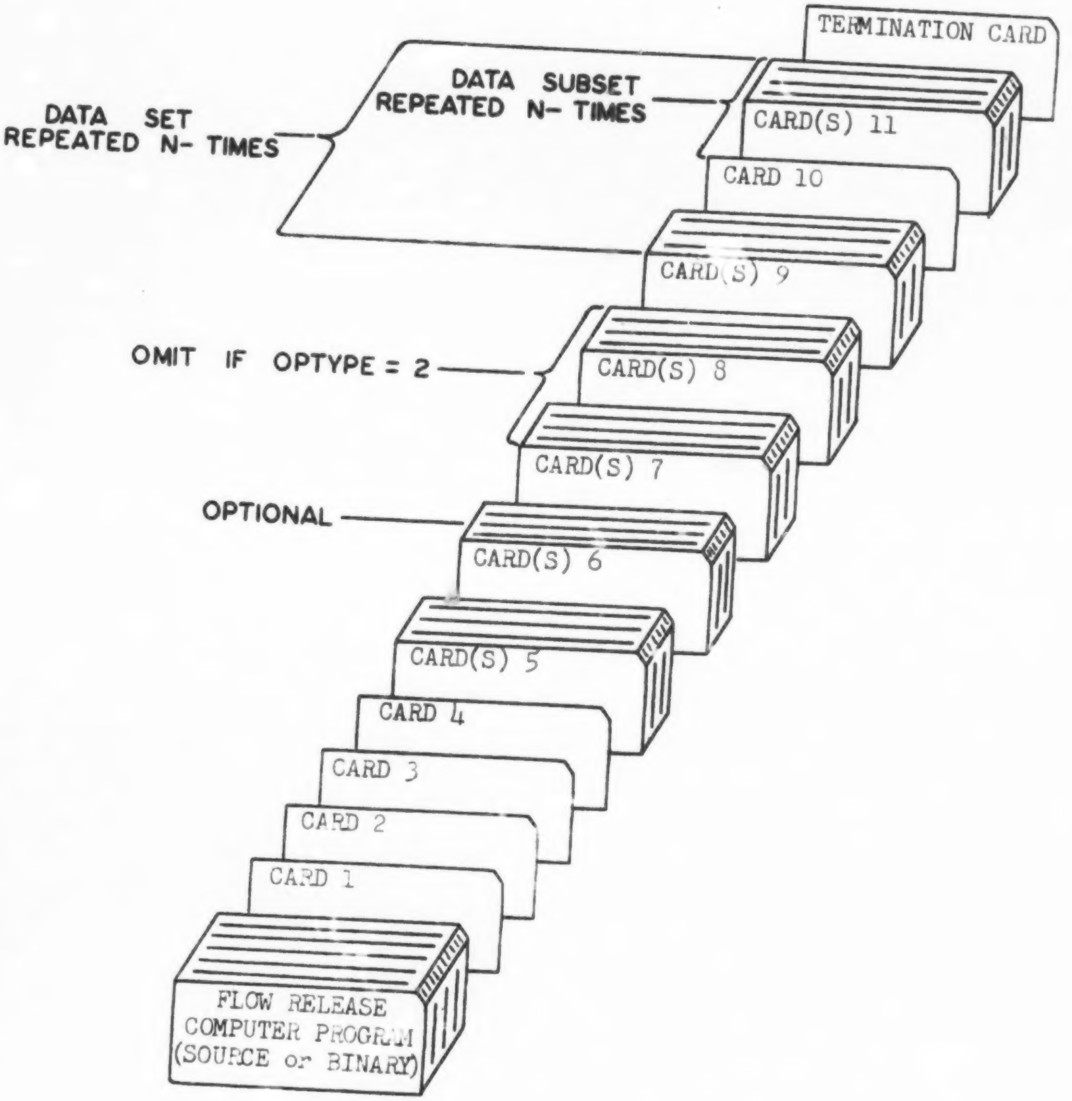

CARD 1
MAIN PARAMETER CARD
TOTALN
TOTALW
TOTALR
TRES
FIRSTI
ITO
IT1
IRMBOD
ITBOD
OPTYPE
IRSET
DELTA
REMBOD
DIS(FIRSTI)
INC
REMPHS
CARD 2
FIVE WASTE TREATMENT LEVELS
WSTP(1)
WSTP(2)
WSTP(3)
WSTP(4)
WSTP(5)
CARD 3
DYNAMIC PROGRAMMING DATA - GRID INCREMENTS
ADD1
ADD2
ADD3
ADD 4
ADD 5
CARD 4
DYNAMIC PROGRAMMING DATA - TEST GRID
TEST 1
TEST 2
TEST 3
TEST 4
TEST 5
CARD 5
PHYSICAL DATA OF STREAM BY SECTIONS
I(N)
J(N)
TDIS(N)
DAREA(N)
AA(N)
BB(N)
CC(N)
DD(N)
NNTYPE(N)
CARD 6
CONTINUATION OF CARD 5 (OPTIONAL)
I(N)
J(N)
SLOPE(N)
DPFAC(N)
CONST(N)
DECAYT(N)
TTEMP(N)
DECAYP(N)
PPHOS(N)
PHOTOS(N)
SLUDGE(N)
EXTBOD(N)
SEDBOD(N)
CARD 7
RESERVOIR INFORMATION
NRES(N)
NRN(N)
MES(N)
IRES(N)
ACREFT(N)
WQACFT(N)
TCOST(N)
WQCOST(N)
AVERESQ(N)
INRESQ(N)
CARD 8
RESERVOIR COST
NRES(N)
CARD
COST
COST
COST
COST
COST
COST
COST
COST
COST
COST
COST
COST
CARD 9
WASTE WATER DISCHARGE DATA
WJ(N)
WTYPE(N)
WWFLOW(N)
WK(N)
WBOD(N)
WDO(N)
WTEMP(N)
WPHOS(N)
WREM(N)
CARD 10
SECONDARY PARAMETER CARD
IT2
TTEMP1
IT3
CONST1
IT 4
DDFAC 1
IT5
DKTEMP
IT6
DKPHOS
IT 7
SSPHOS
IT 8
BODSS
CARD 11
DATA AT STREAM FLOW ADDITION POINTS
RJ(N)
RTYPE(N)
RMNQ(N)
RMAXQ(N)
RBOD(N)
RDO (N)
RPHOS(N)
RK(N)
RTEMP(N)
RFTEMP(N)
RFDOD(N)
RFBOD(N)
RFPHOS

Figure 31


TERMINATION CARD
DATA SUBSET REPEATED N- TIMES
CARD(S) 11
DATA SET REPEATED N- TIMES
CARD 10
CARD(S) 9
OPTIONAL
CARD(S) 6
CARD(S) 5
CARD 2
CARD 1
VERIFICATION LINK COMPUTER PROGRAM (SOURCE or BINARY)

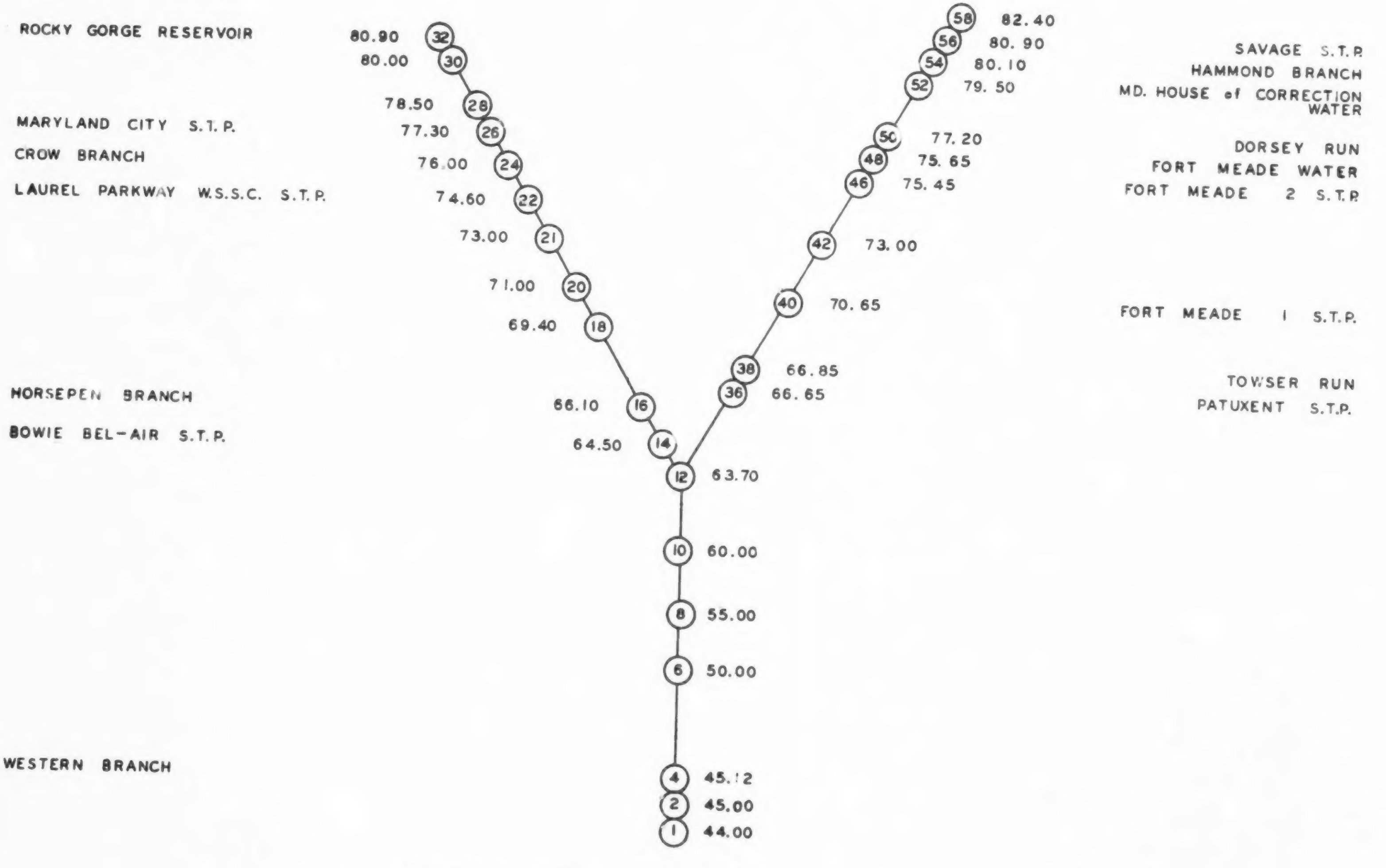
TYPICAL DATA COMPILATION
FOR
VERIFICATION LINK

Figure 32


TERMINATION CARD
DATA SUBSET REPEATED N- TIMES
DATA SET REPEATED N- TIMES
CARD(S) 11
CARD 10
CARD(S) 9
OMIT IF OPTYPE = 2
CARD(S) 8
CARD(S) 7
OPTIONAL
CARD(S) 6
CARD(S) 5
CARD 4
CARD 3
CARD 2
CARD 1
FLOW RELEASE COMPUTER PROGRAM (SOURCE or BINARY)

TYPICAL DATA COMPILATION
FOR
FLOW RELEASE MODEL

Figure 33


ROCKY GORGE RESERVOIR
MARYLAND CITY S.T.P.
CROW BRANCH
LAUREL PARKWAY W.S.S.C. S.T.P.
HORSEPEN BRANCH
BOWIE BEL-AIR S.T.P.
WESTERN BRANCH
80.90
32
80.00
30
78.50
28
77.30
26
76.00
24
74.60
22
73.00
21
71.00
20
69.40
18
66.10
16
64.50
14
12
63.70
10
60.00
8
55.00
6
50.00
4
45.12
2
45.00
1
44.00
58
82.40
56
80.90
54
80.10
52
79.50
50
77.20
48
75.65
46
75.45
42
73.00
40
70.65
38
66.85
36
66.65
SAVAGE S.T.P.
HAMMOND BRANCH
MD. HOUSE of CORRECTION WATER
DORSEY RUN
FORT MEADE WATER
FORT MEADE 2 S.T.P.
FORT MEADE 1 S.T.P.
TOWSER RUN
PATUXENT S.T.P.

PATUXENT RIVER BASIN

Figure 34

```
INPUT DATA FOR FLOW RELEASE MODEL --- PATUXENT RIVER BASIN

23     9    13     2   1     1     1     1     1     1     2    5. 00.0  44.   2.0  0.0
      85.
     1.00       0.80        0.60        0.40        0.2
     4.00       3.00        2.00        1.00        0.00
 1     2      44.990      524.27      0.285       0.440        .050       .483     1
 2     4      45.000      524.27      0.285       0.440        .050       .483     3
 4     6      50.00       414.77      0.285       0.440        .050       .483     3
 6     8      55.000      386.00      0.285       0.440        .050       .483     3
 8    10      60.00       362.00      0.375       0.440       0.047      0.525     3
10    12      63.70       342.60      0.360       0.480       0.056      0.490     2
12    14      64.50       181.20      0.630       0.480       0.075      0.490     3
14    16      66.10       181.20      0.620       0.480       0.075      0.490     3
16    18      69.40       181.20      0.600       0.480       0.075      0.490     3
18    20      71.00        157.0      1.000        .285        .062       .622     1
20    21      73.00        157.0       .850        .285        .062       .622     1
21    22      74.60        157.0       .700        .285        .056       .622     3
22    24      76.00       157.10      0.660       0.285       0.070      0.622     3
24    26      77.30       133.00      0.560       0.285       0.076      0.622     3
26    28      78.50       133.00      0.660       0.285       0.080      0.622     1
28    30      80.00       133.00      0.580       0.273       0.360      0.253     1
30    32      80.90       133.00      0.480       0.273       0.400      0.253     6
32    36      66.65       161.10      0.660       0.320       0.038      0.525     3
36    38      66.85       161.10      0.650       0.320       0.039      0.525     3
38    40      70.65       140.00      0.550       0.320       0.041      0.625     3
40    42      73.00       140.00      0.550       0.320       0.042      0.625     3
42    46      75.45       125.00      0.530       0.343       0.240      0.360     3
46    48      75.65       125.00      0.500       0.343       0.240      0.360     4
48    50      77.20       125.00      0.580       0.285       0.060      0.622     3
```

```
                         CONTINUED
   INPUT DATA FOR FLOW RELEASE MODEL --- PATUXENT RIVER BASIN

 50    52       78.50     110.00       0.580       0.285       0.060       0.622    4
 52    54       80.10     110.00       0.580       0.285       0.060       0.622    3
 54    56       80.90     110.00       0.480       0.285       0.100       0.622    3
 56    58       82.40      98.48       0.330       0.340       0.135       0.525    6
 14     2       1.90         .15       185.0         4.0        25.0        45.0        93.0
 22     2       2.50         .15       136.0         4.0        25.0        31.0        87.0
 26     2        .440        .15       207.0         4.0        25.0        32.0        95.0
 36     2        .700        .15       185.0         4.0        25.0        30.0        95.0
 40     2       1.6          .15       210.0         4.0        25.0        25.0        85.0
 46     2       1.40         .15       310.0         4.0        25.0        27.0        85.0
 48     5       4.000
 52     5       1.000
 56     2       0.300        .15       200.0         4.0        25.0        22.0        85.0
  1  25.0     1   5.0    1   1.6         .25     1   .20     1   .05     1   2.0
  4    0    4.10   4.10   6.50   8.4   .050    .10  25.0
  6    0     .91    .91   3.00   6.0   .050    .10  25.0
  8    0     .91    .91   3.00   6.0   .050    .10  25.0
 10    0     .91    .91   3.00   6.0   .050    .10  25.0
 16    0    1.70   1.70   3.00   6.0   .050    .10  22.0
 18    0    1.70   1.70   3.00   6.0   .050    .10  22.0
 24    0    3.40   3.40   3.00   6.0   .050    .10  22.0
 32    2   15.00  55.00   3.30   8.9   .050    .10  17.0
 36    0    3.46   3.46   3.00   6.0   .050    .10  22.0
 42    0    2.45   2.45   3.00   6.0   .050    .10  22.0
 50    0    2.45   2.45  11.4    3.2 3.0       .10  22.0
 54    0    1.95   1.95   3.00   6.0   .050    .10  22.0
 58    2   15.00  55.00   3.00   6.0   .050    .10  22.0
```

```
                         SAMPLE OUTPUT OF FLOW RELEASE MODEL
                                      INPUT DATA

    STREAM SEGEMENTS           WASTE DISCHARGES          FLOW ADD POINTS           RESERVOI^S
          28                          9                        13                       2

FIRST NODE   REAIR    D-SETS   F-SETS   T-SETS   I-BOD   O-TYPE   INC     DELTA   REMBOD   REMPHS  D-FIRST NODE
    1          2         1        1        1        1       1     2.00     5.00    0.0      0.0      44.00
                                                 STREAM DATA
SECTION  I-NODE  J-NODE   DISTANCE      AREA          AA          BB          CC          DD       TYPE
                          (MILES)    SQ.MILES)

   1        1       2      44.990     524.270       0.285       0.440       0.050       0.483      1
   2        2       4      45.000     524.270       0.285       0.440       0.050       0.483      3
   3        4       6      50.000     414.770       0.285       0.440       0.050       0.483      3
   4        6       8      55.000     386.000       0.285       0.440       0.050       0.483      3
   5        8      10      60.000     362.000       0.375       0.440       0.047       0.525      3
   6       10      12      63.700     342.600       0.360       0.480       0.056       0.490      2
   7       12      14      64.500     181.200       0.680       0.480       0.075       0.490      3
   8       14      16      66.100     181.200       0.620       0.480       0.075       0.490      3
   9       16      18      69.400     181.200       0.600       0.480       0.075       0.490      3
  10       18      20      71.000     157.000       1.000       0.285       0.062       0.622      1
  11       20      21      73.000     157.000       0.850       0.285       0.062       0.622      1
  12       21      22      74.600     157.000       0.700       0.285       0.056       0.622      3
  13       22      24      76.000     157.100       0.660       0.295       0.070       0.622      3
  14       24      26      77.300     133.000       0.660       0.285       0.076       0.622      3
  15       26      28      78.500     133.000       0.660       0.285       0.080       0.622      1
  16       28      30      80.000     133.000       0.580       0.273       0.360       0.253      1
  17       30      32      80.900     133.000       0.480       0.273       0.400       0.253      6
  18       12      36      66.650     161.100       0.660       0.320       0.038       0.625      3
  19       36      38      66.850     161.100       0.660       0.320       0.039       0.625      3
  20       38      40      70.650     140.000       0.550       0.320       0.041       0.625      3
  21       40      42      73.000     140.000       0.550       0.320       0.042       0.625      3
  22       42      46      75.450     125.000       0.530       0.343       0.240       0.360      3
  23       46      48      75.650     125.000       0.500       0.343       0.240       0.360      4
  24       48      50      77.200     125.000       0.580       0.285       0.060       0.622      3
  25       50      52      78.500     110.000       0.580       0.285       0.060       0.622      4
  26       52      54      80.100     110.000       0.580       0.285       0.060       0.622      3
  27       54      56      80.900     110.000       0.480       0.285       0.100       0.622      3
  28       56      58      82.400      98.480       0.330       0.340       0.135       0.525      6
```

```
                                   DYNAMIC PROGRAMMING BASIC DATA

           TEST 1    TEST 2    TEST 3    TEST 4    TEST 5     ADD 1     ADD 2     ADD 3     ADD 4     ADD 5

             4.00      3.00      2.00      1.00      0.0       1.00      0.80      0.60      0.40      0.20
                                                           WASTE DATA
NUMBER    NODE    TYPE        FLOW        DEOX         BOD            DO           TEMP         PHOS         REMOVAL
                              (MGD)      (1/DAY)  (MG/L OR #/DAY)   (MG/L)        (DEG.C)      (MG/L)          (%)

   1       14       2         1.900       0.150      185.000        4.000        25.000       45.000        93.000
   2       22       2         2.500       0.150      136.000        4.000        25.000       31.000        87.000
   3       26       2         0.440       0.150      207.000        4.000        25.000       39.000        95.000
   4       36       2         0.700       0.150      185.000        4.000        25.000       30.000        95.000
   5       40       2         1.600       0.150      210.000        4.000        25.000       25.000        85.000
   6       46       2         1.400       0.150      310.000        4.000        25.000       27.000        85.000
   7       48       5         4.000       0.0          0.0          0.0           0.0          0.0           0.0
   8       52       5         1.000       0.0          0.0          0.0           0.0          0.0           0.0
   9       56       2         0.300       0.150      200.000        4.000        25.000       22.000        85.000
```

```
                                                   ADDITIONAL DATA

IT2   S.S. TEMP.   IT3   DO-CONSTR.   IT4   DEPTH FACT   IT5   DECAY TEMP   IT6   DECAY PHOS   IT7   S.S. PHOS.   IT8   DY EQ BOD.

1       25.00       1       5.00       1       1.60      1       0.25       1       0.20       1       0.05       1       2.00
                                                  STREAM FLOW DATA
NUMBER  NODE   TYPE   MIN-FLOW  MAX-FLOW    BOD       DO       PHOS      DEOX      TEMP     F-TEMP     F-DO      F-BOD     F-PHOS
                       (CFS)     (CFS)     (MG/L)    (MG/L)    (MG/L)   (1/DAY)   (DEG.C)

   1      4      0      4.10      4.10      6.50      8.40      0.05      0.10     25.00      0.0       0.0       0.0       0.0
   2      6      0      0.91      0.91      3.00      6.00      0.05      0.10     25.00      0.0       0.0       0.0       0.0
   3      8      0      0.91      0.91      3.00      6.00      0.05      0.10     25.00      0.0       0.0       0.0       0.0
   4     10      0      0.91      0.91      3.00      6.00      0.05      0.10     25.00      0.0       0.0       0.0       0.0
   5     16      0      1.70      1.70      3.00      6.00      0.05      0.10     25.00      0.0       0.0       0.0       0.0
   6     18      0      1.70      1.70      3.00      6.00      0.05      0.10     22.00      0.0       0.0       0.0       0.0
   7     24      0      3.40      3.40      3.00      6.00      0.05      0.10     22.00      0.0       0.0       0.0       0.0
   8     32      2     15.00     55.00      3.00      6.00      0.05      0.10     22.00      0.0       0.0       0.0       0.0
   9     38      0      3.46      3.46      3.30      8.90      0.05      0.10     17.00      0.0       0.0       0.0       0.0
  10     42      0      2.45      2.45      3.00      6.00      0.05      0.10     22.00      0.0       0.0       0.0       0.0
  11     50      0      2.45      2.45     11.40      3.20      0.05      0.10     22.00      0.0       0.0       0.0       0.0
  12     54      0      1.95      1.95      3.00      6.00      3.00      0.10     22.00      0.0       0.0       0.0       0.0
  13     58      2     15.00     55.00      3.00      6.00      0.05      0.10     22.00      0.0       0.0       0.0       0.0
```

```
                    MINIMUM   TREATMENT

                          85.00

             CALCULATED MIN- & MAX- FLOW DATA

  JJ            RFLOW(JJ)          MINRQ(JJ)           MAXRQ(JJ)

  58              15.00              15.00               55.00
  56              15.46              15.46               55.46
  54              17.41              17.41               57.41
  52              15.87              15.87               55.87
  50              18.32              18.32               58.32
  48              12.13              12.13               52.13
  46              14.29              14.29               54.29
  42              16.74              16.74               56.74
  40              19.22              19.22               59.22
  38              22.68              22.68               62.68
  36              23.76              23.76               63.76
  32              15.00              15.00               55.00
  30              15.00              15.00               55.00
  28              15.00              15.00               55.00
  26              15.68              15.68               55.68
  24              19.08              19.08               59.08
  22              22.95              22.95               62.95
  21              22.95              22.95               62.95
  20              22.95              22.95               62.95
  18              24.65              24.65               64.65
  16              26.35              26.35               66.35
  14              29.29              29.29               69.29
  12              53.05              53.05              133.05
  10              53.96              53.96              133.96
   8              54.87              54.87              134.87
   6              55.78              55.78              135.78
   4              59.88              59.88              139.88
   2              59.88              59.88              139.88
```

```
                                        INCREMENTAL FLOW TABLEAU

                                           U-NODE =  36

  FLOW            BOD             DOD             SAT-DO          DEAIR           TEMP            COST
  (CFS)          (MG/L)          (MG/L)           (MG/L)         (1/DAY)         (DEG.C)        (ANNUAL)

  33.76           4.55            2.93             8.19            0.14           24.89            0.0
  38.76           4.41            2.69             8.19            0.13           24.89            0.0
  43.76           4.29            2.51             8.19            0.13           24.88            0.0
  48.76           4.18            2.36             8.20            0.13           24.87            0.0
  53.76           4.09            2.24             8.20            0.13           24.86            0.0
  58.76           4.00            2.14             8.20            0.13           24.84            0.0
  63.76           3.93            2.06             8.20            0.13           24.82            0.0
```

```
                              INCREMENTAL FLOW TABLEAU

                                   U-NODE =  14
 FLOW          BOD           DOD          SAT-DO          DEAIR          TEMP         COST
(CFS)         (MG/L)        (MG/L)        (MG/L)         (1/DAY)       (DEG.C)      (ANNUAL)

 29.29          3.78          2.82          8.21           0.13          24.81          0.0
 34.29          3.66          2.61          8.21           0.13          24.77          0.0
 39.29          3.57          2.45          8.22           0.13          24.70          0.0
 44.29          3.50          2.31          8.24           0.13          24.61          0.0
 49.29          3.44          2.19          8.25           0.13          24.51          0.0
 54.29          3.40          2.10          8.27           0.12          24.39          0.0
 59.29          3.36          2.01          8.29           0.12          24.27          0.0
 64.29          3.33          1.94          8.31           0.12          24.14          0.0
 69.29          3.31          1.87          8.33           0.12          24.01          0.0
```

```
                                   INCREMENTAL FLOW TABLEAU

                                       U-NODE =    2
  FLOW            BOD             DOD            SAT-DO          DEAIR          TEMP          COST
 (CFS)          (MG/L)          (MG/L)           (MG/L)         (1/DAY)        (DEG.C)       (ANNUAL)

  69.88           2.14            1.24            8.18            0.13          25.00           0.0
  74.88           2.12            1.28            8.18            0.13          25.00           0.0
  79.88           2.11            1.32            8.18            0.13          25.00           0.0
  84.88           2.10            1.35            8.18            0.13          25.00           0.0
  89.88           2.10            1.37            8.18            0.13          25.00           0.0
  94.88           2.09            1.40            8.18            0.13          25.00           0.0
  99.88           2.08            1.42            8.18            0.13          25.00           0.0
 104.88           2.08            1.44            8.18            0.13          25.00           0.0
 109.88           2.07            1.46            8.18            0.12          25.00           0.0
 114.88           2.07            1.48            8.18            0.12          24.99           0.0
 119.88           2.06            1.49            8.18            0.12          24.98           0.0
 124.88           2.06            1.50            8.18            0.12          24.98           0.0
 129.88           2.06            1.52            8.18            0.12          24.98           0.0
 134.88           2.05            1.53            8.18            0.12          24.98           0.0
 139.88           2.05            1.54            8.18            0.12          24.97           0.0
```

```
                                      DYNAMIC PROGRAMMING TABLEAU  1

                                             FOR NODE =  12

TOTAL FLOW    FLOW AT  14    FLOW AT =  36        BOD           DOD          SAT-DO        DEAIR         TEMP         COST
  (CFS)         (CFS)          (CFS)            (MG/L)        (MG/L)        (MG/L)       (1/DAY)      (DEG.C)      (ANNUAL)

   63.05         29.29          33.76            4.19          2.88          8.20          0.14         24.86          0.0
   68.05         29.29          38.76            4.14          2.75          8.20          0.13         24.96          0.0
   73.05         29.29          43.76            4.09          2.63          8.20          0.13         24.85          0.0
   78.05         29.29          48.76            4.03          2.53          8.20          0.13         24.85          0.0
   83.05         29.29          53.76            3.99          2.44          8.20          0.13         24.84          0.0
   88.05         29.29          58.76            3.93          2.37          8.20          0.13         24.83          0.0
   93.05         29.29          63.76            3.88          2.30          8.20          0.13         24.82          0.0
   98.05         34.29          63.76            3.83          2.25          8.21          0.13         24.80          0.0
  103.05         39.29          63.76            3.79          2.21          8.21          0.13         24.78          0.0
  108.05         44.29          63.76            3.75          2.16          8.22          0.13         24.74          0.0
  113.05         69.29          43.76            3.69          2.12          8.28          0.13         24.35          0.0
  118.05         69.29          48.76            3.67          2.07          8.28          0.13         24.36          0.0
  123.05         69.29          53.76            3.65          2.03          8.27          0.13         24.38          0.0
  128.05         69.29          58.76            3.63          2.00          8.27          0.12         24.39          0.0
  133.05         69.29          63.76            3.61          1.96          8.27          0.12         24.40          0.0
```

APPENDIX D

VERIFICATION LINK COMPUTER PROGRAM

```
C                      VERIFICATION LINK - VERSION II
C                                INCLUDES
C             BOD - DO - TEMPERATURE - PHOSPHOROUS ALGORITHMS
C                              DEVELOPED AT
C                         UNIVERSITY OF MICHIGAN
C                          ANN ARBOR, MICHIGAN
C                            FIELD TESTED AT
C                       CHESAPEAKE FIELD STATION
C                                 FWPCA
C                          ANNAPOLIS, MARYLAND
C
      COMMON       AA(350), BB(350), BOD(100), CC(350), CONST(350)
     A           , DAREA(350), DD(350), DECAYP(350), DECAYT(350)
     B           , DEL(100), DEPTH(600), DIS(600), DISTAN(100), DO1(100)
     C           , DOD(100), DPFAC(350), EXTBOD(350), I(350), J(350)
     D           , LBOD(600), LDOD(600), LFLOW(600), LK(600), LPHOS(600)
     E           , LTEMP(600), MAXRQ(600), MINRQ(600), NNTYPE(350)
     F           , PHOS(100), PHOTOS(350), PPHOS(350), RBOD(150)
     G           , RDO(150), REAIR(600), RFBOD(150), RFDO(150)
     H           , RFLOW(600), RFPHOS(150), RFTEMP(150), RJ(150)
     I           , RK(150), RMAXQ(150), RMINQ(150), RPHOS(150)
     J           , RTEMP(150), RTYPE(150), SATDO(100), SBOD(600)
     K           , SEDBOD(350), SFLOW(600), SK(600), SLDBOD(350)
     L           , SLOPE(350), SSBOD(100), SSDOD(100), SSTEMP(100)
     M           , STEMP(600), SXFLOW(100), SYFLOW(100), TDIS(350)
      DIMENSION    TEMP(100), TRET(30), TTEMP(350), VEL(600), WBOD(150)
     A           , WDO(150), WFLOW(600), WIDTH(600), WJ(150), WK(150)
     B           , WPHOS(150), WREM(150), WSTP(5), WTEMP(150)
     C           , WTYPE(150), WWFLOW(150),NN(600),NTYPE(600)
C
C
      INTEGER      BCC, C. D, E, EE, EEE, FIRSTI, RJ, RTYPE, S, SS, T
     A           , TAPE1, TAPE2, TOTALN, TOTALR, TOTALW, TT, W, WJ
     B           , WTYPE, X, XNODE, Y, YBASE, YNODE, YYBASE, Z , TRES
C
      REAL         INC, K, LBOD, LDOD, LFLOW, LK, LPHOS, LTEMP, MAXRQ
     A           , MBOD, MDOD, MFLOW, MINRQ, MK, MPHOS, MTEMP, NBOD
     B           , NDOD, NFLOW, NK, NPHOS, NTEMP
C
      CALL TIMEIN
  001 READ (1,1001) TOTALN, TOTALW, TOTALR, TRES, FIRSTI, ITO, IT1
     B           , IRMBOD, ITBOD, OPTYPE, IRSET, DELTA, REMBOD
     C           , DIS(FIRSTI), INC, REMPHS
      READ (1,1005) WSTP(1), WSTP(2), WSTP(3), WSTP(4), WSTP(5)
      READ(1,1002) (I(N), J(N), TDIS(N), DAREA(N),          AA(N)
     1             ,BB(N), CC(N), DD(N), NNTYPE(N),          N=1,TOTALN)
      WRITE  (3,3050) TOTALN, TOTALW, TOTALR , TRES
      WRITE (3,3060) FIRSTI, IRSET, ITO, IT1 , IRMBOD,   ITBOD, OPTYPE
     A           , INC, DELTA, REMBOD, REMPHS, DIS(FIRSTI)
      WRITE(3,3002) (N, I(N), J(N), TDIS(N), DAREA(N), AA(N), BB(N)
     B            , CC(N), DD(N), NNTYPE(N), N= 1, TOTALN)
   75 READ(1,1003) (WJ(N), WTYPE(N), WWFLOW(N), WK(N), WBOD(N), WDO(N)
     1             ,WTEMP(N), WPHOS(N), WREM(N), N=1,TOTALW)
      WRITE (3,3003)  ( N, WJ(N), WTYPE(N), WWFLOW(N), WK(N), WBOD(N)
     A               , WDO(N), WTEMP(N), WPHOS(N), WREM(N), N=1,TOTALW)
C
      IRM        =  1
      IQM        = 1
      ERROR      =  .005
   78 READ (1,1008) IT2, TTEMP1, IT3, CONST1, IT4, DPFAC1, IT5, DKTEMP,
     A     IT6, DKPHOS, IT7, SSPHOS,IT8,BODSS
      WRITE(3,4010) IT2, TTEMP1, IT3, CONST1, IT4, DPFAC1, IT5, DKTEMP,
     A     IT6, DKPHOS, IT7, SSPHOS,IT8,BODSS
      IF(IRMBOD) 79, 79, 80
   79 WSTP(IRM) = 0.
   80 GO TO (81,83), IT2
   81 DO 82 IJK = 1, TOTALN
   82 TTEMP(IJK)= TTEMP1
   83 GO TO (84,86), IT3
   84 DO 85 IJK = 1, TOTALN
   85 CONST(IJK)= CONST1
   86 GO TO (87,89), IT4
   87 DO 88 IJK = 1, TOTALN
   88 DPFAC(IJK)= DPFAC1
   89 GO TO (90,92), IT5
   90 DO 91 IJK = 1, TOTALN
   91 DECAYT(IJK)= DKTEMP
   92 GO TO (93,95), IT6
   93 DO 94 IJK = 1, TOTALN
   94 DECAYP(IJK)= DKPHOS
   95 GO TO (96,98), IT7
   96 DO 97 IJK = 1, TOTALN
   97 PPHOS(IJK) = SSPHOS
   98 CONTINUE
      GO TO ( 100,102),IT8
  100 DO 101 IJK= 1, TOTALN
  101 SEDBOD( IJK) = BODSS
  102 DO 103 N = 1, TOTALN
      JJ        = J(N)
      NN(JJ)    = N
      DIS(JJ)   = TDIS(N)
  103 NTYPE( JJ ) = NNTYPE( N)
      DO  104    IJK = 1, 600
      RFLOW(IJK) = 0.
      SFLOW(IJK) = 0.
      LFLOW(IJK) = 0.
      WFLOW(IJK) = 0.
      MINRQ(IJK) = 0.
  104 MAXRQ( IJK ) = 0.
      READ(1,1004) (RJ(N), RTYPE(N), RMINQ(N), RMAXQ(N), RBOD(N),RDO(N)
     A              ,RPHOS(N), RK(N), RTEMP(N), RFTEMP(N), RFDO(N)
     B              ,RFBOD(N), RFPHOS(N), N=1,TOTALR)
      WRITE (3,3004) ( N, RJ(N), RTYPE(N), RMINQ(N), RMAXQ(N), RBOD(N)
     A                , RDO(N), RPHOS(N), RK(N), RTEMP(N), RFTEMP(N)
     B                , RFDO(N), RFBOD(N), RFPHOS(N), N = 1, TOTALR )
C
      IRM          =  1
  105 DO 109 N  = 1, TOTALR
      ITR1        =  RTYPE(N) + 1
      JJ         =  RJ(N)
      GO TO (107, 106, 106), ITR1
  106 MINRQ(JJ) = RMINQ(N)
      MAXRQ(JJ) = RMAXQ(N)
      GO TO 109
  107 WFLOW(JJ) = RMINQ(N)
      WW5        =  RMINQ(N) * 5.39
      LFLOW(JJ) =  WFLOW(JJ)
      LBOD(JJ)  =  RBOD(N) * WW5
      LTEMP(JJ) =  RTEMP(N)
      LK(JJ)     =  RK(N)
      LPHOS(JJ) =  RPHOS(N) * WW5
      LDOD(JJ)   = (QSATDO(LTEMP(JJ)) - RDO(N)) * WW5
  109 CONTINUE
  110 DO 120  N = 1, TOTALW
      WSTPX = WREM(N)
      JJ         =  WJ(N)
      IWTP       =  WTYPE(N)
      GO TO (115, 116, 116, 116, 119), IWTP
  115 WW5        =  WWFLOW(N) * 5.39
      LFLOW(JJ) =  WWFLOW(N)
      WFLOW(JJ) =  LFLOW(JJ)
      LBOD(JJ)   =  WBOD(N) * WW5
      LTEMP(JJ) =  WTEMP(N)
      LK(JJ)     =  WK(N)
      LPHOS(JJ) =  WPHOS(N) * WW5
      LDOD(JJ)   = (QSATDO(LTEMP(JJ)) - WDO(N)) * WW5
      GO TO 120
  116 IF (WREM(N)- WSTP(IRM))117, 118, 118
  117 WREM(N)    =  WSTP(IRM)
  118 WW8        =  WWFLOW(N) * 8.345
      LFLOW(JJ) =  WWFLOW(N) * 1.547
      WFLOW(JJ) =  LFLOW(JJ)
      GO TO (112, 113), ITBOD
  113 LBOD(JJ)   =  WBOD(N) * (100. - WREM(N)) / 100.
      GO TO 114
  112 LBOD(JJ)   =  WBOD(N) * (100. - WREM(N)) * WW8 / 100.
  114 LTEMP(JJ)   =  WTEMP(N)
      LK(JJ)     =  WK(N)
      LPHOS(JJ) = WPHOS(N) * WW8 * (100.-REMPHS)/100.
      LDOD(JJ)  = (QSATDO(LTEMP(JJ))- WDO(N)) * WW8
      WREM(N)    =  WSTPX
      GO TO 120
  119 LFLOW(JJ) = -WWFLOW(N) * 1.547
      WFLOW(JJ) =  LFLOW(JJ)
      LBOD(JJ)   =  0.0
      LTEMP(JJ) =  0.0
      LK(JJ)     =  0.0
      LPHOS(JJ) =  0.0
      LDOD(JJ)   =  0.0
  120 CONTINUE
      IF ( IRM -1 ) 136, 136, 137
  136 WRITE ( 3, 2007 )
      DO 140 IJK = 1, TOTALN
      N = TOTALN - IJK + 1
      JJ = J(N)
      II =  I(N)
      MINRQ(JJ) =  MINRQ(JJ) + WFLOW(JJ)
      MAXRQ(JJ) =  MAXRQ(JJ) + WFLOW(JJ)
      MINRQ(II) =  MINRQ(JJ) + MINRQ(II)
      MAXRQ(II) =  MAXRQ(JJ) + MAXRQ(II)
      RFLOW(JJ) =  MINRQ(JJ)
  140 WRITE (3,1007) JJ, RFLOW(JJ), MINRQ(JJ), MAXRQ(JJ)
  137 WRITE ( 3, 5001 ) WSTP(IRM)
      WRITE (3,3015)
C
      L  =  TOTALR
C
   54 IF (RTYPE(L)) 152, 151, 152
  151 L          =  L - 1
      GO TO 54
  152 JJ         =  RJ(L)
      N  =  NN(JJ)
      II =  I(N)
      T  =  1
      TEMP(T)    =  RTEMP(L)
      BOD(T)     =  RBOD(L)
      DO1(T)     =  RDO(L)
      PHOS(T)    =  RPHOS(L)
      SATDO(T)   = QSATDO(TEMP(T))
      DOD(T) = SATDO(T) - DO1(T)
      DEL(T)     = TEMP(T) - TTEMP(N)
      SK(JJ)     = RK(L)
      DISTAN(T) = DIS(JJ)
      R5 = RFLOW(JJ) * 5.39
      LPHOS(JJ) = PHOS(T)*R5
      LFLOW(JJ) = RFLOW(JJ)
      LTEMP(JJ) = TEMP(T)
      LDOD(JJ)  = DOD(T) * R5
      LBOD(JJ)  = BOD(T) * R5
      LK(JJ) = SK(JJ)
C
   51 DEPTH(JJ) = AA(N) * RFLOW(JJ) ** BB(N)
      VEL(JJ)   = CC(N) * RFLOW(JJ) ** DD(N)
      DIST      = DIS(JJ)
      GO TO (191, 192, 193, 194), IRSET
  191 REAIR(JJ) = ((146.8 * VEL(JJ))**.5)/(2.303*(DEPTH(JJ)*DPFAC(N))
     A             ** 1.50 )
      GO TO  50
  192 REAIR(JJ) = (5.026 * VEL(JJ) **.969) /(DPFAC(N)*DEPTH(JJ))**1.673
      GO TO  50
  193 REAIR(JJ) =(3.3 * VEL(JJ))/(( DEPTH(JJ) * DPFAC(N))**1.33)
      GO TO 50
  194 GO TO 9999
C
   50 K          = SK(JJ)
      IF (DIST - DIS(II) - INC) 750, 750, 760
  750 BCC        = 0
      TDIST      = DIST - DIS(II)
      DIST       =  DIS(II)
      GO TO 770
  760 BCC        = 1
      TDIST      = INC
      DIST       = DIST - INC
C
  770 TIME       =  TDIST / (VEL(JJ) * 16.36364)
                 =  T + 1
      DISTAN(T) = DIST
      QQQQ       = -TDIST * DECAYT(N)/ (VEL(JJ) * DEPTH(JJ))
  772 TEMP(T) = TTEMP(N) + DEL(T-1) * EXP(QQQQ)
```

```
      DEL(T)     =  TEMP(T) - TTEMP(N)
      R          =  REAIR(JJ) * 1.0241** (TEMP(T)-20.)
      K          =  K * 1.0471 ** (TEMP(T) - 20.)
      A          =  1. / 10. ** (K * TIME)
      P          =  1. / 10. ** (R * TIME/2.)
      BOD(T)     =  A * BOD(T-1)
      UBOD       = 1. / ( 1.- 10.**(-K * 5.))
      DOD(T)      = P * UBOD *(BOD(T-1)-BOD(T)) + P * P * DOD(T-1)
      SATDO(T)   = QSATDO(TEMP(T))
      DO1(T)     =  SATDO(T) - DOD(T)
      IF(BOD(T) -SEDBOD(N))222,223,223
  222 BOD(T)    = SEDBOD(N)
  223 IF ( DO1( T) ) 224,224,225
  224 DOD(T)     = SATDO(T)
      DO1(T)     = 0.
  225 PHOS(T)    = PHOS(T-1) * 10. ** (-DECAYP(N) * TIME)
      IF (PHOS(T)- PPHOS(N)) 226, 227, 227
  226 PHOS(T)    =  PPHOS(N)
  227 CONTINUE
C
      IF (BCC) 50, 780, 50
C
  780 WRITE (3,3021) (JJ, KKK, RFLOW(JJ), DISTAN(KKK), BOD(KKK)
     A               , TEMP(KKK), SATDO(KKK), DO1(KKK), PHOS(KKK)
     B               , KKK = 1, T )
C
      IF ( I(N) - FIRSTI ) 790, 1260, 790
  790 IF (I(N) - J(N-1)) 800,  53, 800
C
  800 R5          =  RFLOW(JJ) * 5.39
      LBOD(II)   =  BOD(T)  * R5
      LDOD(II)   =  DOD(T)  * R5
      LPHOS(II)  =  PHOS(T) * R5
      LK(II)      = K / (1.047 ** (TEMP(T) - 20.))
      LTEMP(II)  =  TEMP(T)
      LFLOW(II)  =  RFLOW(JJ)
      L           =  L - 1
C     WRITE (3,1009) LFLOW(II), LBOD(II), LDOD(II), LPHOS(II), LTEMP(II)
C    A             , LK(II), II
      GO TO 54
C
   53 TT          =  T
      T           =  1
      III         =  JJ
      JJ          =  II
      N           =  NN(JJ)
      II         =  I(N)
      NT = NTYPE(JJ)
      GO TO (55, 1250, 1250, 55, 1240), NT
      GO TO 51
C
 1240 R5          = RFLOW(III) * 5.39
      K           = K / (1.0471 ** (TEMP(TT)- 20.))
      LK(JJ)      = K
      LBOD(JJ)    = LBOD(JJ) + R5 * BOD(TT) +  LFLOW(JJ) * 5.39 * BOD(TT)
      LPHOS(JJ) = LPHOS(JJ) + R5 * PHOS(TT) + LFLOW(JJ) * 5.39*PHOS(TT)
      LDOD(JJ)    = LDOD(JJ) + R5 * DOD(TT)
      LTEMP(JJ) = (RFLOW(III)*TEMP(TT)+LTEMP(JJ)*LFLOW(JJ))/RFLOW(JJ)
      LFLOW(JJ) = RFLOW(JJ)
      TEMP(T)     = LTEMP(JJ)
      DEL(T)      = TEMP(T) - TTEMP(N)
      SATDO(T)    = QSATDO(TEMP(T))
      R5D         = 1.0 / (RFLOW(JJ) * 5.39)
      BOD(T)      = LBOD(JJ)  * R5D
      DOD(T)      = LDOD(JJ)  * R5D
      PHOS(T)     = LPHOS(JJ) * R5D
      DO1(T)      = SATDO(T) - DOD(T)
      DISTAN(T) = DIS(JJ)
      SK(JJ)      = LK(JJ)
      GO TO 51
C
   55 TEMP(T)     = TEMP(TT)
      DEL(T)      = DEL(TT)
      SATDO(T)    = SATDO(TT)
      BOD(T)      = BOD(TT)
      DOD(T)      = DOD(TT)
      DO1(T)      = DO1(TT)
      PHOS(T)     = PHOS(TT)
      DISTAN(T) = DIS(JJ)
      SK(JJ)      = SK(III)
      R5          = RFLOW(JJ) * 5.39
      LPHOS(JJ) = PHOS(T)*R5
      LFLOW(JJ) = RFLOW(JJ)
      LTEMP(JJ) = TEMP(T)
      LK(JJ)      = K / (1.0471 ** (TEMP(T) - 20. ))
      LDOD(JJ)    = DOD(T) * R5
      LBOD(JJ)    = BOD(T) * R5
      GO TO 51
C
 1250 R5          =  RFLOW(III)  * 5.39
      K           =  K / (1.0471 ** (TEMP(TT) - 20.))
      LK(JJ)      = (LK(JJ)*LBOD(JJ) + R5*BOD(TT)*K)/(LBOD(JJ)+R5*BOD(TT))
      LBOD(JJ)  =  LBOD(JJ)  + R5 * BOD(TT)
      LDOD(JJ)  =  LDOD(JJ)  + R5 * DOD(TT)
      LPHOS(JJ) =  LPHOS(JJ) + R5 * PHOS(TT)
      LTEMP(JJ) =  (RFLOW(III) * TEMP(TT) + LTEMP(JJ) * LFLOW(JJ)) /
     A             RFLOW(JJ)
      LFLOW(JJ) = RFLOW(JJ)
      TEMP(T)   =  LTEMP(JJ)
      DEL(T)      =  TEMP(T) - TTEMP(N)
      SATDO(T)  = QSATDO(TEMP(T))
      R5D       =  1.0 / (RFLOW(JJ) * 5.39)
      BOD(T)    =  LBOD(JJ)  * R5D
      DOD(T)    =  LDOD(JJ)  * R5D
      PHOS(T)   =  LPHOS(JJ) * R5D
      DOI(T)    =  SATDO(T) - DOD(T)
      DISTAN(T)  =  DIS(JJ)
      SK(JJ)     =  LK(JJ)
      GO TO 51
C
 1260 WRITE (3,3016)
C
      DO  1265  KK = 1, TOTALN
      N          =  TOTALN - KK + 1
      JJ         =  J(N)
 1265 WRITE (3,3006) JJ, LFLOW(JJ), LBOD(JJ), LDOD(JJ), LPHOS(JJ)
     A              , LTEMP(JJ), LK(JJ)
C
      IF (IRMBOD-IRM) 1320, 1320, 1318
 1318 IRM        = IRM + 1
      DO 1319 JJ= 1, 600
      LFLOW(JJ) = 0.
      LDOD(JJ)  = 0.
      LBOD(JJ)  = 0.
      LTEMP(JJ) = 0.
      LK(JJ)    = 0.
 1319 LPHOS(JJ) = 0.
      GO TO 105
 1320 WRITE (3,3007)
      DO  1321 KK = 1, TOTALN
      N  =  TOTALN - KK+ 1
      JJ = J(N)
      IY    =    I(N)
      IX        =  J(N)
      DIST      = DIS(IX)-DIS(IY)
      TIME      = DIST /(VEL(JJ)* 16.36364)
 1321 WRITE (3,3008) JJ, RFLOW(JJ), SK(JJ), REAIR(JJ), VEL(JJ)
     A              , DEPTH(JJ), TIME
```

```
      IF( IT1-IQM) 1400, 1400, 1325
 1325 DO 1330 JJ= 1, 600
      LFLOW(JJ) = 0.
      LBOD(JJ)  = 0.
      LDOD(JJ)  = 0.
      LTEMP(JJ) = 0.
      LK(JJ)    = 0.
      RFLOW(JJ) = 0.
      MINRQ(JJ) = 0.
      MAXRQ(JJ) = 0.
 1330 WFLOW(JJ) = 0.
      IQM       = IQM + 1
      GO TO 78
 1400 IF(ITO-1)   1500, 1500, 1450
 1450  ITO      = ITO - 1
      GO TO 75
 1500 WRITE (3,3000)
C      FORMAT STATEMENTS
 1001 FORMAT ( 11I5, 5F5.0)
C
 1002 FORMAT ( 2I5, 6F10.0, I5)
 1003 FORMAT ( 2I5, 7F10.0     )
 1004 FORMAT ( 2I4, 1X, 11F6.2)
 1005 FORMAT ( 8F10.2 )
 1006 FORMAT( 6F12.2)
 1007 FORMAT ( ' ' 34X I3, 3F20.2 )
 1008 FORMAT ( 7( I5, F5.0))
 1009 FORMAT ( '0                    LFLOW(II)                        LBOD(II)                LDO
     AD(II)                 LPHOS(II)                     LTEMP(II)                     LK(II)
     B  II ' / 6F20.2, I5 )
C
 1050 FORMAT ( 4I5,6F10.0)
 1090 FORMAT ( 10X, 7F5.0 )
 2002 FORMAT ( 3I5, 6F10.2, I5 )
 2003 FORMAT ( 3I5, 7F10.2        )
 2004 FORMAT ( 3I4, 1X, 11F6.2 )
 2005 FORMAT ( ' END OF JOB ' )
 2007 FORMAT ( '1' 49X 'CALCULATED MIN- & MAX- FLOW DATA' /
     A          '0' 35X 'JJ' 12X ' RFLOW(JJ)' 11X 'MINRQ(JJ)' 11X
     B          'MAXRQ(JJ)' // )
C
 3000 FORMAT('1' 10X 'END OF JOB')
C
 3002 FORMAT ( '1' 60X 'STREAM DATA' / '0' 4X 'SECTION' 3X 'I-NODE' 3X
     A          'J-NODE' 6X 'DISTANCE' 9X 'AREA' 12X 'AA' 14X 'BB' 13X
     B          'CC' 13X 'DD' 8X 'TYPE' / ' ' 35X '(MILES)' 7X
     C          '(SQ.MILES)' // (' ' 3I9, 6F15.3, I9))
 3003 FORMAT ( '1' 60X ' WASTE DATA' / '0' 5X 'NUMBER' 4X 'NODE' 5X
     A          'TYPE' 9X 'FLOW' 11X 'DEOX' 11X 'BOD' 13X 'DO' 12X 'TEMP'
     B          11X 'PHOS' 9X 'REMOVAL' /38X '(MGD)' 8X '(1/DAY)' 5X
     C          '(MG/L OR #/DAY)' 4X '(MG/L)' 8X '(DEG.C)' 9X '(MG/L)'
     D          10X '(%)' // (1H 3I9, 7F15.3))
 3004 FORMAT ( '1' 57X 'STREAM FLOW DATA' / '0' '   NUMBER  NODE   TYPE'
     A           '    MIN-FLOW  MAX-FLOW    BOD' 8X 'DO' 7X 'PHOS' 6X
     B           'DEOX' 6X 'TEMP     F-TEMP     F-DO      F-BOD      '
     C           'F-PHOS' / 27X '(CFS)       (CFS)      (MG/L)     (MG/L)'
     D           '      (MG/L)    (1/DAY)   (DEG.C)' // (' ' 3I7, 11F10.2) )
 3005 FORMAT ( ' ' / (2I10, 7F15.2))
 3006 FORMAT (  I10, 6F20.2)
 3007 FORMAT ( '1' 49X 'CALCULATED STREAM CHARACTERISTICS'   /
     A          '0' 6X 'NODE' 14X 'FLOW' 16X 'DEOX' 16X 'REAIR' 13X
     B         'VELOCITY' 14X 'DEPTH'  14X     'D-TIME'//
     C         25X '(CFS)' 14X '(1/DAY)' 13X '(1/DAY)' 14X  '(FPS)'
     D         15X '(FEET)'  14X '(DAYS)'//)
 3008 FORMAT  ( I10, 6F20.3)
 3011 FORMAT ( '1' 49X 'CALCULATED MIN- & MAX- FLOW DATA' / '0' 35X
     A          'JJ' 13X 'RFLOW(JJ)' 11X 'MINRQ(JJ)' 11X 'MAXRQ(JJ)' // )
 3012 FORMAT ( ' ' 32X I5, 3F20.2)
 3015 FORMAT ( '0' 50X 'CALCULATED STREAM QUALITY DATA'  /
     A          '0', 6X 'NODE' 8X 'T' 10X 'FLOW' 9X 'DISTANCE' 10X 'BOD'
     B          11X 'TEMP' 11X 'SATDO' 11X 'DO' 12X 'PHOS' / 30X '(CFS)'
     C          9X '(MILES)' 8X '(MG/L)' 9X '(DEG.C)' 8X '(MG/L)' 9X
     D         '(MG/L)' 9X '(MG/L)' )
 3016 FORMAT ( '1' 56X 'CALCULATED NODE DATA'  /
     A          '0' 6X 'NODE' 14X 'FLOW' 16X 'BOD' 17X 'DOD' 16X 'PHOS'
     A          17X 'TEMP' 16X 'DEOX' / 25X '(CFS)' 13X '(#/DAY)' 13X
     B          '(#/DAY)' 13X '(#/DAY)' 14X '(DEG.C)' 12X '(1/DAY)' // )
 3021 FORMAT ('0' / (I10, I10, 2F15.2, F14.2, 4F15.2 ))
C
 3050 FORMAT ('1' 58X 'INPUT DATA' /// 10X 'STREAM SEGEMENTS' 15X
     A          'WASTE DISCHARGFS' 15X 'FLOW ADD POINTS' 17X
     B          'RESERVOIRS' // I20, 3I30)
 3060 FORMAT ('0'/ ' ' 3X 'FIRST NODE' 3X 'REAIR' 5X 'D-SETS' 4X'F-SETS'
     A           4X 'T-SETS' 4X 'I-BOD' 4X 'O-TYPE' 4X 'INC' 6X 'DELTA' 5X
     B          'REMBOD' 4X 'REMPHS' 2X 'D-FIRST NODE'// 7I10, 5F10.2 )
 4001 FORMAT ( 3I10, F15.3, I10 )
 4010 FORMAT ('1' 60X 'ADDITIONAL DATA'//'0' 1X 'IT2' 3X 'S.S. TEMP.'
     A         3X 'IT3' 3X 'DO-CONSTR.' 3X 'IT4'  3X  'DEPTH FACT' 3X
     B         'IT5' 3X 'DECAY TEMP' 3X 'IT6' 3X 'DECAY PHOS' 3X 'IT7'
     C         3X 'S.S. PHOS.' 3X 'IT8' 3X 'DY EQ BOD.' //'0'
     D         2X, I1,  F11.2, 6%I8, F11.2<<
C
```

```
 5001 FORMAT ('1' 54X 'MINIMUM % TREATMENT' // ( 62X F5.2 ))
 8000 FORMAT ( 5X, F5.0, 7F10.0 )
C
      CALL TIMED
 9999 STOP
      END
      FUNCTION QSATDO(TEMP)
C
      QSATDO    =  14.652 - (0.41022    * TEMP)
     A                    + (.007991    * TEMP * TEMP)
     B                    - (.77774E-4 * TEMP * TEMP * TEMP)
C
      RETURN
      END
```

APPENDIX E

OPTIMAL FLOW RELEASE MODEL COMPUTER PROGRAM

```
C                     OPTIMAL FLOW RELEASE MODEL - VERSION II
C                                    INCLUDES
C                        BOD - DO - TEMPERATURE ALGORITHMS
C                                      WITH
C                               COST OF RESERVOIRS
C                                  DEVELOPED AT
C                             UNIVERSITY OF MICHIGAN
C                              ANN ARBOR, MICHIGAN
C                                FIELD TESTED AT
C                            CHESAPEAKE FIELD STATION
C                                     FWPCA
C                              ANNAPOLIS, MARYLAND
C
      COMMON       AA(320), ACREFT(20), AVRESQ(20), BB(320), BOD(100)
     A           , CC(320), CONST(320), DAREA(320), DD(320), DECAYP(350)
     B           , DECAYT(350), DEL(100), DEPTH(600), DIS(600)
     C           , DISTAN(100), DO1(100), DOD(100), DPFAC(320)
     D           , EXTBOD(350), I(320), INRESQ(20), IRES(20), J(320)
     E           , LBOD(600), LDOD(600), LFLOW(600), LK(600), LPHOS(600)
     F           , LTEMP(600), MAXM(30), MAXRQ(600), MBOD(200)
     G           , MCOST(200), MDOD(200), MFLOW(200), MINRQ(600), MJ(30)
     H           , MK(200), MN(30), MRES(20), MTEMP(200), NBOD(200)
     I           , NCOST(200), NDOD(200), NFLOW(200), NK(200), NN(600)
     J           , NNTYPE(320), NRES(20), NRJ(600), NTEMP(200), NRN(20)
     K           , NTYPE(600), OBOD(200), OCOST(200), ODOD(200)
     L           , OFLOW(200), OK(200), OTEMP(200), OXFLOW(200)
      DIMENSION    OYFLOW(200), PHOS(100), PHOTOS(350), PPHOS(350)
     A           , RBOD(100), RCOST(20,100), RDO(100), REAIR(600)
     B           , RFBOD(100), RFDO(100), RFLOW(600), RFPHOS(100)
     C           , RFTEMP(100), RJ(100), RK(100), RMAXQ(100), RMINQ(100)
     D           , RPHOS(100), RTEMP(100), RTYPE(100), SATDO(100)
     E           , SBOD(600), SCOST(200), SDELL(600), SDOD(600)
     F           , SEDBOD(350), SFLOW(600), SK(600), SLOBOD(350)
     G           , SLOPE(350), SSBOD(100), SSDOD(100), SSTEMP(100)
     H           , STEMP(600), SXFLOW(100), SYFLOW(100), TCOST(20)
     I           , TDIS(320), TEMP(100), TRET(30), TTEMP(320), VEL(600)
     J           , WBOD(100), WDO(100), WFLOW(600), WIDTH(600), WJ(100)
     K           , WK(100), WPHOS(100), WOACFT(20), WOCOST(20), WSTP(5)
     L           , WREM(100), WTEMP(100), WTYPE(100), WWFLOW(100)
C
      INTEGER      BCC, C, D, E, EE, EEE, FIRSTI, RJ, RTYPE, S, SS, T
     A           , TAPE1, TAPE2, TOTALN, TOTALR, TOTALW, TT, W, WJ
     B           , WTYPE, X, XNODE, Y, YBASE, YNODE, YYBASE, Z,TRES
     C           , OPTYPE, OPT
C
```

```
      REAL          INC, K, LBOD, LDOD, LFLOW, LK, LPHOS, LTEMP, MAXRQ
     A            , MBOD, MDOD, MFLOW, MINRQ, MK, MPHOS, MTEMP, NBOD
     B            , NDOD, NFLOW, NK, NPHOS, NTEMP
     C            , MCOST, NCOST, OCOST , INRESQ
  001 CALL TIMEIN
      IRM        =1
      TAPE1      =  7
      TAPE2      =  9
      ERROR      = .005
      NE         =  0
      IOM        = 1
      READ (1,1001) TOTALN, TOTALW, TOTALR, TRES, FIRSTI, ITO, IT1   ,
     A      IRMBOD,ITBOD, OPTYPE, IRSET, DELTA, REMBOD, DIS(FIRSTI),
     B      INC, REMPHS
      READ (1,1005) WSTP(1), WSTP(2), WSTP(3), WSTP(4), WSTP(5)
      READ (1,1005) ADD1, ADD2, ADD3, ADD4, ADD5
      READ (1,1005) TEST1, TEST2, TEST3, TEST4,TEST5
      READ(1,1002) (I(N), J(N), TDIS(N), DAREA(N),            AA(N)
     1            ,BB(N), CC(N), DD(N), NNTYPE(N),            N=1,TOTALN)
C
      WRITE  (3,3050) TOTALN, TOTALW, TOTALR , TRES
      WRITE (3,3060) FIRSTI, IRSET, ITO, IT1 , IRMBOD,   ITBOD, OPTYPE,
     A       INC, DELTA, REMBOD, REMPHS, DIS(FIRSTI)
      WRITE(3,3002) (N, I(N), J(N), TDIS(N), DAREA(N), AA(N), BB(N)
     B            , CC(N), DD(N), NNTYPE(N), N= 1, TOTALN)
C
      WRITE (3,3013) TEST1, TEST2, TEST3, TEST4, TEST5, ADD1, ADD2,
     A              ADD3, ADD4, ADD5
      IF(OPTYPE-1)75,75,72
   72 READ (1,4050) (NRES(N), NRN(N), MRES(N), IRES(N), ACREFT(N),
     A      WQACFT(N), TCOST(N), WQCOST(N), AVRESQ(N), INRESQ(N),
     B      N = 1, TRES)
      WRITE (3,3070) ( NRES(N), NRN(N), IRES(N), MRES(N), ACREFT(N),
     A       WQACFT(N), TCOST(N), WQCOST(N), AVRESQ(N), INRESQ(N),
     B       N= 1, TRES)
      DO 73 IXY  = 1, TRES
      IXP        = NRN(IXY)
      NRJ(IXP)   = IXY
      IZY        = 1
      IZT        = 12
      MCP        = MRES(IXY)
      DO 73 IZX  = 1, MCP
      READ(1,8005) (RCOST(IXY,IZZ), IZZ = IZY, IZT)
      IZY        =  IZY + 12
      IZT        =  IZT + 12
   73 CONTINUE
```

```
 75 READ(1,1003) (WJ(N), WTYPE(N), WWFLOW(N), WK(N), WBOD(N), WDO(N)
   1             ,WTEMP(N), WPHOS(N), WREM(N), N=1,TOTALW)
    WRITE (3,3003)  ( N, WJ(N), WTYPE(N), WWFLOW(N), WK(N), WBOD(N)
   A             , WDO(N), WTEMP(N), WPHOS(N), WREM(N), N=1,TOTALW)
    IQM        = 1
 78 READ (1,1008) IT2, TTEMP1, IT3, CONST1, IT4, DPFAC1, IT5, DKTEMP,
   A     IT6, DKPHOS, IT7, SSPHOS,IT8,BODSS
    WRITE(3,4010) IT2, TTEMP1, IT3, CONST1, IT4, DPFAC1, IT5, DKTEMP,
   A     IT6, DKPHOS, IT7, SSPHOS,IT8,BODSS
    IF(IRMBOD) 79, 79, 80
 79 WSTP(IRM) = 0.
 80 GO TO (81,83), IT2
 81 DO 82 IJK = 1, TOTALN
 82 TTEMP(IJK)= TTEMP1
 83 GO TO (84,86), IT3
 84 DO 85 IJK = 1, TOTALN
 85 CONST(IJK)= CONST1
 86 GO TO (87,89), IT4
 87 DO 88 IJK = 1, TOTALN
 88 DPFAC(IJK)= DPFAC1
 89 GO TO (90,92), IT5
 90 DO 91 IJK = 1, TOTALN
 91 DECAYT(IJK)= DKTEMP
 92 GO TO (93,95), IT6
 93 DO 94 IJK = 1, TOTALN
 94 DECAYP(IJK)= DKPHOS
 95 GO TO (96,98), IT7
 96 DO 97 IJK = 1, TOTALN
 97 PPHOS(IJK) = SSPHOS
 98 GO TO ( 100,102),IT8
100 DO 101 IJK= 1, TOTALN
101 SEDBOD( IJK) = BODSS
102 DO 103 N = 1, TOTALN
    JJ         = J(N)
    NN(JJ)     = N
    DIS(JJ)    = TDIS(N)
103 NTYPE( JJ ) = NNTYPE( N)
    DO  104   IJK = 1, 600
    RFLOW(IJK) = 0.
    SFLOW(IJK) = 0.
    LFLOW(IJK) = 0.
    WFLOW(IJK) = 0.
    MINRQ(IJK) = 0.
104 MAXRQ( IJK ) = 0.
    READ(1,1004) (RJ(N), RTYPE(N), RMINQ(N), RMAXQ(N), RBOD(N),RDO(N)
   A             ,RPHOS(N), RK(N), RTEMP(N), RFTEMP(N), RFDO(N)
```

```
     2        ,RFBOD(N), RFPHOS(N), N=1,TOTALR)
      WRITE (3,3004) ( N, RJ(N), RTYPE(N), RMINQ(N), RMAXQ(N), RBOD(N)
     A               , RDO(N), RPHOS(N), RK(N), RTEMP(N), RFTEMP(N)
     B               , RFDO(N), RFBOD(N), RFPHOS(N), N = 1, TOTALR )
C
      IRM         = 1
  105 DO 109 N   = 1, TOTALR
      JJ          =  RJ(N)
      ITR1          =  RTYPE(N) + 1
      GO TO (107, 106, 106), ITR1
  106 MINRQ(JJ) = RMINQ(N)
      MAXRQ(JJ) = RMAXQ(N)
      GO TO 109
  107 WFLOW(JJ) = RMINQ(N)
      WW5         =  RMINQ(N) * 5.39
      LFLOW(JJ) =  WFLOW(JJ)
      LBOD(JJ)    =  RBOD(N) * WW5
      LTEMP(JJ) =  RTEMP(N)
      LK(JJ)      =  RK(N)
      LPHOS(JJ) =  RPHOS(N) * WW5
      LDOD(JJ)  = (QSATDO(LTEMP(JJ)) - RDO(N)) * WW5
  109 CONTINUE
  110 WRITE (3,5001) WSTP(IRM)
      NE          = 0
      REWIND TAPE1
      REWIND TAPE2
      DO 120  N = 1, TOTALW
      WSTPX = WREM(N)
      JJ          =  WJ(N)
      IWTP        =  WTYPE(N)
      GU TO (115, 116, 116, 116, 119), IWTP
  115 WW5         =  WWFLOW(N) * 5.39
      LFLOW(JJ) =  WWFLOW(N)
      WFLOW(JJ) =  LFLOW(JJ)
      LBOD(JJ)    =  WBOD(N) * WW5
      LTEMP(JJ) =  WTEMP(N)
      LK(JJ)      =  WK(N)
      LPHOS(JJ) =  WPHOS(N) * WW5
      LDOD(JJ)  = (QSATDO(LTEMP(JJ)) - WDO(N)) * WW5
      GO TO 120
  116 IF (WREM(N)- WSTP(IRM))117, 118, 118
  117 WREM(N)     =  WSTP(IRM)
  118 WW8         =  WWFLOW(N) * 8.345
      LFLOW(JJ) =  WWFLOW(N) * 1.547
      WFLOW(JJ) =  LFLOW(JJ)
      GO TO (112, 113), ITBOD
  113 LBOD(JJ) =  WBOD(N) * (100. - WREM(N))/ 100.
      GO TO 114
  112 LBOD(JJ) =  WBOD(N) * (100. - WREM(N)) * WW8 / 100.
  114 LTEMP(JJ)  =  WTEMP(N)
      LK(JJ)     =  WK(N)
      LPHOS(JJ) = WPHOS(N) * WW8 * (100.-REMPHS)/100.
      LDOD(JJ)  = (QSATDO(LTEMP(JJ))- WDO(N)) * WW8
      WREM(N) = WSTPX
      GO TO 120
  119 LFLOW(JJ) = -WWFLOW(N) * 1.547
      WFLOW(JJ) =  LFLOW(JJ)
      LBOD(JJ)  =  0.0
      LTEMP(JJ) =  0.0
      LK(JJ)    =  0.0
      LPHOS(JJ) =  0.0
      LDOD(JJ)  =  0.0
  120 CONTINUE
      DO 160 IJK = 1, TOTALN
      N = TOTALN - IJK + 1
      JJ = J(N)
      II = I(N)
      MAXRQ(JJ) = MAXRQ(JJ) + WFLOW(JJ)
      MAXRQ(II) = MAXRQ(II) + MAXRQ(JJ)
      MINRQ(JJ) = MINRQ(JJ) + WFLOW(JJ)
      MINRQ(II) = MINRQ(II) + MINRQ(JJ)
  160 RFLOW(JJ) = MINRQ(JJ)
      IF( IRM-1) 161,161,163
  161 WRITE (3,2007)
      DO 162 IJK = 1, TOTALN
      N = TOTALN - IJK + 1
      JJ = J(N)
  162 WRITE (3,1007) JJ, RFLOW(JJ), MINRQ(JJ), MAXRQ(JJ)
C
  163 L          =  TOTALR + 1
    4 L          =  L - 1
      IF (L) 5, 5, 189
  189 IF (RTYPE(L) - 1) 4, 190, 4
C
  190 JJ = RJ(L)
      N  =  NN(JJ)
      II =  I(N)
      T  = 1
      TEMP(T)  = RTEMP(L)
      BOD(T)      = RBOD(L)
      DO1(T)   = RDO(L)
      PHOS(T)  = RPHOS(L)
      SATDO(T) = QSATDO(TEMP(T))
      DOD(T)   = SATDO(T) - DO1(T)
      DEL(T)    = TEMP(T) - TTEMP(N)
      SK(JJ)    = RK(L)
      DISTAN(T) = DIS(JJ)
C
   51 DEPTH(JJ) = AA(N) * RFLOW(JJ) ** BB(N)
      VEL(JJ)   = CC(N) * RFLOW(JJ) ** DD(N)
      DIST      = DIS(JJ)
      GO TO (191, 192, 193, 194), IRSET
  191 REAIR(JJ) = ((146.8 * VEL(JJ))**.5)/(2.303*(DEPTH(JJ)*DPFAC(N))
     A             ** 1.50 )
  192 REAIR(JJ) = (5.026 * VEL(JJ) **.969) /(DPFAC(N)*DEPTH(JJ))**1.673
      GO TO  50
  193 REAIR(JJ) =(3.3 * VEL(JJ))/(( DEPTH(JJ) * DPFAC(N))**1.33)
      GO TO 50
  194 GO TO 9999
C
   50 K         = SK(JJ)
      IF (DIST - DIS(II) - INC) 200, 200, 210
  200 BCC       = 0
      TDIST     = DIST - DIS(II)
      DIST      =  DIS(II)
      GO TO 220
  210 BCC       = 1
      TDIST     = INC
      DIST      = DIST - INC
C
  220 TIME      =  TDIST / (VEL(JJ) * 16.36364)
      T         =  T + 1
      DISTAN(T) = DIST
      QQQQ      = -TDIST * DECAYT(N) / (VEL(JJ) * DEPTH(JJ))
      TEMP(T) = TTEMP(N) + DEL(T-1)* EXP(QQQQ)
      DEL(T)    =  TEMP(T) - TTEMP(N)
      R         =  REAIR(JJ) * 1.0241** (TEMP(T)-20.)
      K         =  K * 1.0471 ** (TEMP(T) - 20.)
      A         =  1. / 10. ** (K * TIME)
      P         =  1. / 10. ** (R * TIME/2.)
      BOD(T)    =  A * BOD(T-1)
      UBOD      = 1. / ( 1.- 10.**(-K * 5.))
      DOD(T)    = P * UBOD * (BOD(T-1) - BOD(T)) + P * P * DOD(T-1)
      SATDO(T)  = QSATDO(TEMP(T))
      IF(BOD(T) -SEDBOD(N))222,223,223
  222 BOD(T)   = SEDBOD(N)
  223 IF ( DO1( T) ) 224,224,225
  224 DOD(T)    = SATDO(T)
```

```
      DO1(T)     = 0.
  225 PHOS(T)    = PHOS(T-1) * 10. ** (-DECAYP(N) * TIME)
      IF (PHOS(T)- PPHOS(N)) 226, 227, 227
  226 PHOS(T)    =  PPHOS(N)
  227 CONTINUE
C
      IF (BCC) 50, 230, 50
C 230 WRITE (3,5002) JJ, RFLOW(JJ), SK(JJ), REAIR(JJ), VEL(JJ)
C    A              , DEPTH(JJ), ( KKK, DISTAN(KKK), BOD(KKK), TEMP(KKK)
C    B              , SATDO(KKK), DO1(KKK), PHOS(KKK), KKK = 1, T)
  230 IF ( I(N) - FIRSTI ) 240, 1260, 240
  240 IF ( I(N) - J(N-1)) 260, 250, 260
  250 IF ( MAXRQ(II) - MINRQ(II) - ERROR) 53, 53, 260
C
  260 R5          =  RFLOW(JJ) * 5.39
      LBOD(II)    =  BOD(T)   * R5
      LDOD(II)    =  DOD(T)   * R5
      LPHOS(II) =  PHOS(T) * R5
      LK(II)     = K / (1.047 ** (TEMP(T) - 20.))
      LTEMP(II) =  TEMP(T)
      LFLOW(II) =  RFLOW(JJ)
      L           =  L - 1
  270 IF(L) 189, 5, 189
C
   53 TT = T
      T  = 1
      III= JJ
      JJ = II
      N  = NN(JJ)
      NTP1        =  NTYPE(JJ)
      II = I(N)
      GO TO (55, 290, 290, 55, 280), NTP1
      GO TO 51
  280 R5          = RFLOW(JJ) * 5.39
      K           = K / (1.0471 ** (TEMP(TT)- 20.))
      LK(JJ)      = (LK(JJ)*LBOD(JJ) + (R5 + 5.39*LFLOW(JJ))*BOD(TT)*K)/
     A              (LBOD(JJ) + (R5 + 5.39*LFLOW(JJ))*BOD(TT))
      LBOD(JJ)    = LBOD(JJ) + R5 * BOD(TT) +  LFLOW(JJ) * 5.39 * BOD(TT)
      LPHOS(JJ) = LPHOS(JJ) + R5 * PHOS(TT) + LFLOW(JJ) * 5.39*PHOS(TT)
      LDOD(JJ)    = LDOD(JJ) + R5 * DOD(TT)
      LTEMP(JJ) = (RFLOW(III)*TEMP(TT)+LTEMP(JJ)*LFLOW(JJ))/RFLOW(JJ)
      TEMP(T)     = LTEMP(JJ)
      DEL(T)      = TEMP(T) - TTEMP(N)
      SATDO(T)    = QSATDO(TEMP(T))
      R5D         = 1.0 / (RFLOW(JJ) * 5.39)
      BOD(T)      = LBOD(JJ)  * R5D
      DOD(T)    = LDOD(JJ)  * R5D
      PHOS(T)   = LPHOS(JJ) * R5D
      DO1(T)    = SATDO(T) - DOD(T)
      DISTAN(T) = DIS(JJ)
      SK(JJ)    = LK(JJ)
      GO TO 51
C
C         TO BE FORMULATED LATER
C
   55 TEMP(T)    =  TEMP(TT)
      DEL(T)     =  DEL(TT)
      SATDO(T)   =  SATDO(TT)
      BOD(T)     =  BOD(TT)
      DOD(T)     =  DOD(TT)
      DO1(T)     =  DO1(TT)
      PHOS(T)    =  PHOS(TT)
      DISTAN(T)  =  DIS(JJ)
      SK(JJ)     = SK(III)
      GO TO 51
C
  290 R5        =  RFLOW(III)  * 5.39
      K         =  K / (1.0471 ** (TEMP(TT) - 20.))
      LK(JJ)    = (LK(JJ)*LBOD(JJ) + R5*BOD(TT)*K)/(LBOD(JJ)+R5*BOD(TT))
      LBOD(JJ)  =  LBOD(JJ)  + R5 * BOD(TT)
      LDOD(JJ)  =  LDOD(JJ)  + R5 * DOD(TT)
      LPHOS(JJ) =  LPHOS(JJ) + R5 * PHOS(TT)
      LTEMP(JJ)  = (RFLOW(III) * TEMP(TT) + LTEMP(JJ) *  LFLOW(JJ)
     A                        ) / RFLOW(JJ)
      TEMP(T)    =  LTEMP(JJ)
      DEL(T)     =  TEMP(T) - TTEMP(N)
      SATDO(T)  = QSATDO(TEMP(T))
      R5D       =  1.0 / (RFLOW(JJ) * 5.39)
      BOD(T)    =  LBOD(JJ)  * R5D
      DOD(T)    =  LDOD(JJ)  * R5D
      PHOS(T)   =  LPHOS(JJ) * R5D
      DO1(T)     =  SATDO(T) - DOD(T)
      DISTAN(T)  =  DIS(JJ)
      SK(JJ) = LK(JJ)
      GO TO 51
C
    5 E = 0
      L = TOTALR
  380 IF (RTYPE( L) - 2) 390, 400, 390
  390 L  = L-1
      IF (L) 30, 30, 380
  400 E  = E + 1
```

```
      D  = 1
      C = 0
      EF = 0
      LLL= RJ( L)
C
  410 JJ = RJ(L)
      N  = NN(JJ)
      II = I(N)
      T  = 1
      EED        =  EE * DELTA
      SFLOW(JJ) =  MINRO(JJ) + EED
      SF5        =  SFLOW(JJ) * 5.39
      SSBOD(T)  = (RBOD(L) + EED * RFBOD(L)) * SF5
      SSTEMP(T) =  RTEMP(L) + EED * RFTEMP(L)
      DO1(T)     =  RDO(L) + EED * RFDO(L)
      SATDO(T)  = QSATDO(SSTEMP(T))
      DOD(T)     = SATDO(T) - DO1(T)
      SSDOD(T)  =  DOD(T) * SF5
      DEL(T)     = SSTEMP(T) - TTEMP(N)
      SK(JJ)     =  RK(L)
      IF (OPTYPE - 2) 405, 406, 405
  405 XCOST=0.
      GO TO 14
  406 CONTINUE
      NRA        = NRJ(JJ)
      ICR        = (EE*DELTA)/IRES(NRA)
      IF (ICR) 408, 408, 407
  407 XCOST      =  RCOST(NRA,ICR)
      GO TO 14
  408 XCOST      = 0.
C
   14 DEPTH(JJ) = AA(N) * SFLOW(JJ) ** BB(N)
      VEL(JJ)    = CC(N) * SFLOW(JJ) ** DD(N)
      DIST       = DIS(JJ)
      GO TO ( 401, 402, 403, 404 ), IRSET
  401 REAIR(JJ) = ((146.8 * VEL(JJ))**.5)/(2.303*(DEPTH(JJ)*DPFAC(N))
     A              ** 1.50 )
      GO TO  6
  402 REAIR(JJ) = (5.026 * VEL(JJ)**.969) / (DPFAC(N)*DEPTH(JJ))** 1.63
      GO TO  6
  403 REAIR(JJ) =(3.3 * VEL(JJ))/(( DEPTH(JJ) * DPFAC(N))**1.33)
      GO TO 6
  404 GO TO 9999
C
    6 IF (DIST - DIS(II) - INC) 420, 420, 430
C
```

```
  420 BCC = 0
      TIME       = (DIST - DIS(II)) / (VEL(JJ) * 16.36364)
      TDIST =  DIST - DIS(II)
      GO TO 440
C
  430 BCC   = 1
      TIME       =  INC / (VEL(JJ) * 16.36364)
      TDIST = INC
      DIST  = DIST - INC
C
  440 T = T + 1
      QQQQ        = -TDIST * DECAYT(N)/ (VEL(JJ) * DEPTH(JJ))
      SSTEMP(T) = TTEMP(N) + DEL(T-1)* EXP(QQQQ)
      DEL(T) =  SSTEMP(T) - TTEMP(N)
      R  =  REAIR(JJ)  *  1.0241 **(SSTEMP(T) - 20.)
      K  =   SK(JJ) *  1.0471 **(SSTEMP(T) - 20.)
      A  =   1. / 10. **  (K * TIME)
      P  =   1. / 10. **  (R * TIME / 2.)
      SSBOD(T) = A * SSBOD(T-1)
      UBOD        = 1. / ( 1.- 10.**(- K    * 5.))
      SSDOD(T)   = P * UBOD * (SSBOD(T-1)-SSBOD(T)) + P*P *SSDOD(T-1)
      SF8         =  (SFLOW(JJ) * 5.39)
      IF ( SSBOD(T)/SF8-SEDBOD(N))447,447,448
  447 SSBOD(T)   =  SEDBOD(N) * SF8
  448 SATDO(T)   = QSATDO(SSTEMP(T) )
      DOD(T)   = SSDOD(T) / (SFLOW(JJ) * 5.39)
      DO1(T)   = SATDO(T) - DOD(T)
C
      IF (DO1(T) - CONST(N)) 450, 460, 460
C
  450 IF (C) 8, 9, 8
C
  460 IF (BCC) 6, 7, 6
C
C 460 IF (BCC) 6, 461, 6
C 461 IF (D-2) 462, 462, 7
C 462 WRITE (3,6001) JJ, SFLOW(JJ), SK(JJ), REAIR(JJ), VEL(JJ),
C    A           DEPTH(JJ), (KKK, SSTEMP(KKK), SSBOD(KKK), SATDO(KKK),
C    B           DO1(KKK), KKK = 1, T)
C     GO TO 7
C6001 FORMAT ( '1' I3, 5F20.2///(I3, 4F20.2))
C
    8 IF (EE + 1 - S )      470, 470, 12
  470 EE = EE + 1
C
  480 JJ = JJJJ
```

```
      N  = NN(JJ)
      II = I(N)
      T  = 1
      OF5         =  OFLOW(EE) * 5.39
      SSBOD(T)  =  OBOD(EE) * OF5
      SSDOD(T)  =  ODOD(EE) * OF5
      SSTEMP(T) = OTEMP(EE)
      SK(JJ)  = OK(EE)
      SFLOW(JJ) = OFLOW(EE)
      SATDO(T) = QSATDO(SSTEMP(T))
      DOD(T)    = ODOD(EE)
      DO1(T)    = SATDO(T) - DOD(T)
      DEL(T)    = SSTEMP(T) - TTEMP(N)
      XCOST=OCOST(EE)
      GO TO 14
C
    9 IF (MINRQ(LLL)+(EE+1)*DELTA-MAXRQ(LLL)) 490, 490, 12
C
  490 EE = EE + 1
      GO TO 410
C
   10 IF (MINRQ(LLL)+(EE+1)*DELTA-MAXRQ(LLL)) 500, 500, 12
C
  500 EE = EE + 1
      D  = D  + 1
      GO TO 410
C
   11 IF (EE+1- S )     510, 510, 12
C
  510 EE = EE + 1
      D  = D  + 1
      GO TO 480
C
   20 JJJJ = JJ
      AFLOW = OFLOW(1) - MINRQ(JJ)
      C    = 1
      E    = E + 1
      D    = 1
      EE  =  1
      GO TO 480
C
    7 IF (II - FIRSTI) 530, 520, 530
  520 IF (MAXRQ(JJ)-SFLOW(JJ)-ERROR) 553, 553, 554
  530 IF (II - J(N-1)) 540, 560, 540
  540 IF (MAXRQ(II)-MINRQ(II)-MAXRQ(JJ)+MINRQ(JJ)-ERROR) 17, 17, 550
C
```

```
  554 III    = JJ
      JJ     = II
      NNN    = N
      GO TO 18
  553 MJ(E) = LASTJ
      K  = K / ( 1.047 ** ( SSTEMP(T) - 20.))
      MFLOW(D) = SFLOW(III)
       MBOD(D) = SSBOD(T)
       MDOD(D) = SSDOD(T)
      MTEMP(D) =SSTEMP(T)
      MK(D)   = K
      MCOST(D)    = XCOST
      MN(E) = LASTN
      MAXM(E) = D
      WRITE(TAPE1) E, MJ(E), MAXM(E), MN(E), (MFLOW(IJK), MBOD(IJK),
     A        MDOD(IJK), MK(IJK), MTEMP(IJK), MCOST(IJK), IJK = 1, D)
      GO TO 30
  550 III = JJ
      JJ  = II
      NNN = N
      N   = NN(JJ)
      II = I(N)
      GO TO 18
C
  560 NTP        =  NTYPE(II)
      GO TO (570, 15, 17, 600, 605), NTP
  570 III = JJ
      SFLOW(II) = SFLOW(JJ)
      JJ  = II
      SFLOW(JJ) = SFLOW(II)
      N = NN(JJ)
      II = I(N)
      SK(JJ) = SK(III)
      SDELL(JJ) = DEL(T)
      STEMP(JJ) = SSTEMP(T)
      SBOD(JJ) = SSBOD(T)
      SDOD(JJ) = SSDOD(T)
      T = 1
      SSBOD(T) = SBOD(JJ)
      SSDOD(T) = SDOD(JJ)
      SSTEMP(T) = STEMP(JJ)
      DEL(T) = SDELL(JJ)
      SATDO(T) = QSATDO(SSTEMP(T))
      DOD(T) = SSDOD(T) /(SFLOW(JJ) * 5.39)
      DO1(T) = SATDO(T) - DOD(T)
      GO TO 14
```

```
C
  600 III = JJ
      JJ  = II
      N   = NN(JJ)
      II = I(N)
      IF (C) 610, 620, 610
  610 SFLOW(JJ) = MINRQ(JJ) + OFLOW(EE) - OFLOW(I) + AFLOW
      GO TO 630
  620 SFLOW(JJ) = MINRQ(JJ) + (EE * DELTA)
  630 SK(JJ) = SK(III)
      SFR       =  SFLOW(JJ) /  SFLOW( III )
      SBOD(JJ)  =  SSBOD(T) * SFR
      SDOD(JJ)  =  SSDOD(T) * SFR
      SDELL(JJ) = DEL(T)
      STEMP(JJ)= SSTEMP(T)
      T = 1
      SSBOD(T) = SBOD(JJ)
      SSDOD(T) = SDOD(JJ)
      SSTEMP(T)= STEMP(JJ)
      DEL(T) = SSTEMP(T) - TTEMP(N)
      DOD(T) = SSDOD(T) / (SFLOW(JJ) * 5.39)
      SATDO(T) = OSATDO(SSTEMP(T))
      DO1(T)    = SATDO(T) - DOD(T)
      GO TO 14
C
   17 III = JJ
      JJ  = II
      N   = NN(JJ)
      II  = I(N)
C
   16 IF (C) 640, 650, 640
  640 SFLOW(JJ) = MINRQ(JJ) + OFLOW(EE) - OFLOW(I) + AFLOW
      GO TO 660
  650 SFLOW(JJ) = MINRQ(JJ) + (EE * DELTA)
C
  660 K = K / 1.047 ** (SSTEMP(T) - 20.)
      SBOD(JJ)  = LBOD(JJ) + SSBOD(T)
      SDOD(JJ)  = LDOD(JJ) + SSDOD(T)
      SK(JJ)    = (LK(JJ)*LBOD(JJ) + SSBOD(T)*K) / SBOD(JJ)
      STEMP(JJ) = (LTEMP(JJ)*LFLOW(JJ) + SSTEMP(T)*SFLOW(III))/SFLOW(JJ)
      SDELL(JJ) = DEL(T)
      T  =  1
      SSBOD(T)  = SBOD(JJ)
      SSDOD(T)  = SDOD(JJ)
      SSTEMP(T) = STEMP(JJ)
      DEL(T)    = SSTEMP(T) - TTEMP(N)
      SATDO(T) = QSATDO(SSTEMP(T))
      DOD(T)    = SSDOD(T) / (SFLOW(JJ)*5.39)
      DO1(T)    = SATDO(T) - DOD(T)
C
      IF (DO1(T)-CONST(N))670, 14, 14
  670 IF (C) 8, 9, 8
C
  605 III       = JJ
      JJ        = II
      N         = NN(JJ)
      II        = I(N)
      IF (C) 607, 606, 607
  607 SFLOW(JJ) = MINRQ(JJ) + OFLOW(EE) - OFLOW(1) + AFLOW
      GO TO 608
  606 SFLOW(JJ) = MINRQ(JJ) + (EE * DELTA)
  608 K         = K / 1.047 ** (SSTEMP(T) - 20.)
      SBOD(JJ)  = LBOD(JJ) + SSBOD(T) + SSBOD(T) * (LFLOW(JJ)        /
     A            SFLOW(III))
      SDOD(JJ)  = LDOD(JJ) + SSDOD(T)
      SK(JJ)    =   K
      STEMP(JJ) = (LTEMP(JJ)*LFLOW(JJ) + SSTEMP(T)*SFLOW(III))/SFLOW(JJ)
      SDELL(JJ) = DEL(T)
      T         = 1
      SSBOD(T)  = SBOD(JJ)
      SSDOD(T)  = SDOD(JJ)
      SSTEMP(T) = STEMP(JJ)
      DEL(T)    = SSTEMP(T) - TTEMP(N)
      SATDO(T)  = QSATDO(SSTEMP(T))
      DOD(T)    = SSDOD(T) / (SFLOW(JJ)*5.39 )
      DO1(T)    = SATDO(T) - DOD(T)
      IF (DO1(T)-CONST(N))609, 14, 14
  609 IF (C) 8, 9, 8
   15 III = JJ
      JJ  = II
      NNN = N
      N   = NN(JJ)
      II  =I(N)
C
      IF ( MAXRQ(JJ ) - MINRQ(JJ ) - MAXRQ(III) + MINRQ(III) - ERROR)
     A      16, 16, 18
C
   18 K  = K / ( 1.047 ** ( SSTEMP(T) - 20.))
      MFLOW(D) = SFLOW(III)
       MBOD(D) = SSBOD(T)
       MDOD(D) = SSDOD(T)
      MTEMP(D) =SSTEMP(T)
      MK(D)    = K
      MCOST(D)    = XCOST
      LASTJ    = JJ
      LASTN    = NNN
      IF(C) 11, 10, 11
C
   12 IF (D-1) 671, 671, 672
  671 WRITE (3,3011)
      E # E -1
      GO TO 30
  672 MJ(E)       = LASTJ
C
      MAXM(E)     = D
      MN(E)       = LASTN
      MMAXM       = D
      MMN         = LASTN
C
      WRITE(TAPE1) E, MJ(E), MAXM(E), MN(E), (MFLOW(IJK), MBOD(IJK),
     A        MDOD(IJK), MK(IJK), MTEMP(IJK), MCOST(IJK), IJK = 1, D)
      EEE         =  E
  680 IF (EEE-1) 999, 390, 685
  685 IF (MJ(E) - MJ(EEE-1)) 690, 19, 690
  690 EEE         =  EEE - 1
      IF (EEE-1) 999, 390, 685
   19 REWIND TAPE1
      IE          =  EEE - 2
      IF (IE) 693, 693, 691
  691 DO 692 IJK = 1, IE
  692 READ (TAPE1)
  693 READ (TAPE1) IXE, LASTJ, NMAXM, NMN, (NFLOW(IJK), NBOD(IJK)
     A       ,NDOD(IJK), NK(IJK), NTEMP(IJK), NCOST(IJK), IJK = 1, NMAXM)
      IF (E - EEE + 1) 999, 696, 694
  694 DO  695 IJK = EEE, E
  695 READ (TAPE1)
C
  696 S  = 1
      SS = 1
      X  = 1
      Y  = 1
      OFLOW(S)   = MFLOW(X) + NFLOW(Y)
      OF15       =  1. / (OFLOW(S) * 5.39)
      OBOD(S)    = (MBOD(X) + NBOD(Y)) * OF15
      ODOD(S)    = (MDOD(X) + NDOD(Y)) * OF15
      OK(S)      = (MK(X)*MBOD(X) + NK(Y)*NBOD(Y)) / (MBOD(X)+NBOD(Y))
      OTEMP(S)   = (MTEMP(X)*MFLOW(X) + NTEMP(Y)*NFLOW(Y)) / OFLOW(S)
      OXFLOW(S) = MFLOW(X)
```

C

```
      OYFLOW(S) = NFLOW(Y)
      OCOST(S)  = MCOST(X) + NCOST(Y)
      RFLOW(JJ) = OFLOW(S)
C
   28 RFLOW(JJ) = RFLOW(JJ) + DELTA
      SS        = 1
      IF (MAXRQ(JJ) - RFLOW(JJ) - ERROR) 711, 711, 712
C
  711 S         = S + 1
      X         =  MMAXM
      Y         =  NMAXM
      OFLOW(S)  = MFLOW(X) + NFLOW(Y)
      OF15      =  1. / (OFLOW(S) * 5.39)
      OBOD(S)   = (MBOD(X) + NBOD(Y)) * OF15
      ODOD(S)   = (MDOD(X) + NDOD(Y)) * OF15
      OK(S)     = (MK(X)*MBOD(X) + NK(Y)*NBOD(Y)) / (MBOD(X) + NBOD(Y))
      OTEMP(S)  = (MTEMP(X)*MFLOW(X) + NTEMP(Y)*NFLOW(Y)) / OFLOW(S)
      OXFLOW(S) = MFLOW(X)
      OYFLOW(S) = NFLOW(Y)
      OCOST(S)  = MCOST(X) + NCOST(Y)
C
      XNODE =  J(MMN)
      YNODE =  J(NMN)
      WRITE (TAPE2) LASTJ, S, XNODE, YNODE, (OFLOW(IJK), OBOD(IJK)
     A          , ODOD(IJK), OK(IJK), OTEMP(IJK), OXFLOW(IJK)
     B          , OYFLOW(IJK), OCOST(IJK), IJK = 1, S)
      NE        =  NE + 1
      GO TO 20
C
  712 X         =  1
      Y         = NMAXM
      GO TO 21
C
C
   21 IF (MFLOW(X) + NFLOW(Y) - RFLOW(JJ)+ERROR ) 810, 830, 830
  810 IF (X - MMAXM) 820, 830, 820
C
  820 X = X + 1
      GO TO 21
C
  830 SFLOW(SS) = MFLOW(X) + NFLOW(Y)
      IF (SFLOW(SS) - RFLOW(JJ) - ERROR) 840, 840, 850
C
  840 YBASE     = Y
      GO TO 22
C
```

```
  850 IF (NFLOW(Y-1) + MFLOW(X) - RFLOW(JJ) + ERROR ) 22, 860, 860
C
  860 Y          = Y-1
      YBASE      = Y
      GO TO 850
C
   22 SFLOW(SS) = MFLOW(X) + NFLOW(Y)
      SXFLOW(SS)= MFLOW(X)
      SYFLOW(SS)=  NFLOW(Y)
      SF15      =  1. / (SFLOW(SS) * 5.39)
      SBOD(SS)  = (MBOD(X) + NBOD(Y)) * SF15
      SDOD(SS)  = (MDOD(X) + NDOD(Y)) * SF15
      SK(SS)    = (MK(X)*MBOD(X) + NK(Y)*NBOD(Y)) / (MBOD(X) + NBOD(Y))
      STEMP(SS) = (MTEMP(X)*MFLOW(X) + NTEMP(Y)*NFLOW(Y)) / SFLOW(SS)
      SCOST(SS) = MCOST(X) + NCOST(Y)
C
      IF (Y - NMAXM) 870, 890, 870
  870 IF (NFLOW(Y+1)-NFLOW(Y)-ERROR) 880, 880, 890
  880 Y = Y+1
      SS = SS+1
      GO TO 22
C
  890 IF (X - MMAXM) 900, 23, 900
  900 IF (MFLOW(X+1)-MFLOW(X)-ERROR) 910, 910, 23
  910 X = X+1
      SS = SS+1
      Y = YBASE
      GO TO 22
C
   23 X  = X + 1
      Y  = YBASE - 1
      SS = SS + 1
C
  920 SFLOW(SS)  =  MFLOW(X) + NFLOW(Y)
      IF (ABS(SFLOW(SS)-RFLOW(JJ))-ERROR) 24, 24, 930
  930 IF (X+1-MMAXM) 940, 940, 931
  931 SS         =  SS - 1
      GO TO 25
  940 IF (MFLOW(X+1)-MFLOW(X)-ERROR) 950, 950, 960
C
  950 X = X + 1
      Y = YBASE - 1
      GO TO 920
C
  960 Y      = YYBASE
      X      = X + 1
```

C

```
      YBASE = Y + 1
      GO TO 920
C
   24 SXFLOW(SS) =  MFLOW(X)
      SYFLOW(SS) =  NFLOW(Y)
      SF15       =  1. / (SFLOW(SS) * 5.39)
      SBOD(SS)   = (MBOD(X) + NBOD(Y)) * SF15
      SDOD(SS)   = (MDOD(X) + NDOD(Y)) * SF15
      SK(SS)      = (MK(X)*MBOD(X) + NK(Y)*NBOD(Y)) / (MBOD(X) + NBOD(Y))
      STEMP(SS)  = (MTEMP(X)*MFLOW(X)+NTEMP(Y)*NFLOW(Y)) / SFLOW(SS)
      SCOST(SS) = MCOST(X) + NCOST(Y)
C
      IF (Y - 1) 980, 980, 970
C
  970 Y      =  Y - 1
      SS     =  SS + 1
      YYBASE=  Y
      GO TO 920
C
  980 IF (X + 1 - MMAXM) 990, 990, 25
C
  990 IF (MFLOW(X+1) - MFLOW(X) - ERROR) 1000, 1000, 25
  999 STOP 9999
C
 1000 X  =  X + 1
      SS =  SS + 1
      GO TO 24
C
   25 MAXSS       =  SS
 1010 MMMMM       =  MAXSS - 1
      DO 1030  W = 1, MMMMM
      MWMWM       =  MAXSS - W  + 1
      DO   26  Z = 2, MWMWM
      IF (SBOD(Z) - SBOD(Z-1)) 1020, 26, 26
 1020 SF          = SFLOW(Z)
      SFLOW(Z)    = SFLOW(Z-1)
      SFLOW(Z-1) = SF
      SB          = SBOD(Z)
      SBOD(Z)     = SBOD(Z-1)
      SBOD(Z-1)   = SB
      SD          = SDOD(Z)
      SDOD(Z)     = SDOD(Z-1)
      SDOD(Z-1)   = SD
      SSK         = SK(Z)
      SK(Z)       = SK(Z-1)
      SK(Z-1)     = SSK
      ST          = STEMP(Z)
      STEMP(Z)    = STEMP(Z-1)
      STEMP(Z-1) = ST
      SX          = SXFLOW(Z)
      SXFLOW(Z)   = SXFLOW(Z-1)
      SXFLOW(Z-1)= SX
      SY          = SYFLOW(Z)
      SYFLOW(Z)   = SYFLOW(Z-1)
      SYFLOW(Z-1) = SY
      SC          = SCOST(Z)
      SCOST(Z)   = SCOST(Z-1)
      SCOST(Z-1)= SC
   26 CONTINUE
 1030 CONTINUE
C
C
      OBMAX  =  SBOD(SS)
      OBMIN  =  SBOD(1)
      TEST   =  OBMAX - OBMIN
C
      IF (TEST - TEST1) 1050, 1050, 1040
 1040 ADD          =  ADD1
      GO TO 27
C
 1050 IF (TEST - TEST2) 1070, 1070, 1060
 1060 ADD          =  ADD2
      GO TO 27
C
 1070 IF (TEST - TEST3) 1090, 1090, 1080
 1080 ADD          =  ADD3
      GO TO 27
C
 1090 IF (TEST - TEST4) 1110, 1110, 1100
 1100 ADD          =  ADD4
      GO TO 27
C
 1110 ADD          =  ADD5
C
   27 IXC  =  1
      SS   =  1
      S    =  S + 1
      COMPAR      =  SBOD(1)
 1120 OFLOW(S)    =  SFLOW(SS)
      OBOD(S)     =  SBOD(SS)
      ODOD(S)     =  SDOD(SS)
      OK(S)       =  SK(SS)
      OTEMP(S)   =  STEMP(SS)
      OYFLOW(S)  =  SYFLOW(SS)
      OXFLOW(S)  =  SXFLOW(SS)
      OCOST(S)  = SCOST(SS)
      S  =  S + 1
      IF (S - 200) 29, 29, 1200
   29 SS =  SS + 1
      IF (SS - MAXSS) 1140, 1140, 1130
 1130 S  =  S - 1
      GO TO 28
 1140 IF (SBOD(SS) - COMPAR - ADD) 1160, 1150, 1150
 1150 IXC  =  0
      COMPAR  =  COMPAR + ADD
      GO TO 1140
 1160 IF (IXC - 1) 1170, 1180, 1170
 1170 IXC  =  1
      GO TO 1120
 1180 OPT= OPTYPE
      GO TO (1185, 1186, 1187), OPT
 1185 IF(SDOD(SS)-ODOD(S-1 ))1190, 29, 29
 1186 IF(SCOST(SS)-OCOST(S-1 )) 1190, 29, 29
 1187 STOP 8888
 1190 S  =  S - 1
      GO TO 1120
C
 1200 WRITE (3,3017)
      GO  TO 30
C
C
C
C
 1260 CONTINUE                                                    C
      WRITE (3,8010)
   30 REWIND TAPE1
      DO 1300 IJK = 1, E
      READ (TAPE1) EEE, MJ(EEE), D, MN(EEE), (MFLOW(JKL),  MBOD(JKL)
     A          , MDOD(JKL), MK(JKL), MTEMP(JKL), MCOST(JKL), JKL= 1, D)
      KLM       =  MN(EEE)
      DO 1290  JKL =1,D
      RD5    =1./(5.39*MFLOW(JKL))
      MBOD(JKL)=MBOD(JKL) *RD5
      MDOD(JKL)=MDOD(JKL) *RD5
 1290 SATDO(JKL)= QSATDO(MTEMP(JKL))
 1300 WRITE (3,3014)  J(KLM), (MFLOW(JKL), MBOD(JKL), MDOD(JKL),
     A        SATDO(JKL), MK(JKL), MTEMP(JKL), MCOST(JKL), JKL = 1, D)
C
```

```
      IF(NE)1316,1316,1304
 1304 REWIND TAPE2
C
      DO 1310 IJK = 1, NE
      READ (TAPE2) LASTJ, S, XNODE, YNODE, (OFLOW(JKL), OBOD(JKL)
     A            , ODOD(JKL), OK(JKL), OTEMP(JKL), OXFLOW(JKL)
     B      ,OYFLOW(JKL), OCOST(JKL), JKL = 1, S)
      DO 1305 IJT = 1, S
 1305 SATDO(IJT)  = QSATDO(OTEMP(IJT))
 1310  WRITE (3,3015) IJK, LASTJ, XNODE, YNODE, (OFLOW(JKL), OXFLOW(JKL)
     A            , OYFLOW(JKL), OBOD(JKL), ODOD(JKL), SATDO(JKL)
     B            , OK(JKL), OTEMP(JKL), OCOST(JKL), JKL = 1, S)
 1316 IF (IRMBOD-IRM) 1320, 1320, 1318
 1318 IRM        = IRM + 1
      DO 1319 JJ= 1, 600
      LFLOW(JJ) = 0.
      LDOD(JJ)  = 0.
      LBOD(JJ)  = 0.
      LTEMP(JJ) = 0.
      LK(JJ)    = 0.
      RFLOW(JJ) = 0.
      MINRQ(JJ) = 0.
      MAXRQ(JJ) = 0.
      WFLOW(JJ) = 0.
 1319 LPHOS(JJ) = 0.
      GO TO 105
 1320 IF( IT1-IQM) 1400, 1400, 1325
 1325 DO 1330 JJ= 1, 600
      LFLOW(JJ) = 0.
      LBOD(JJ)  = 0.
      LDOD(JJ)  = 0.
      LTEMP(JJ) = 0.
      LK(JJ)    = 0.
      RFLOW(JJ) = 0.
      MINRQ(JJ) = 0.
      MAXRQ(JJ) = 0.
 1330 WFLOW(JJ) = 0.
      IQM       = IQM+1
      GO TO 78
 1400 IF (ITO-1) 1500, 1500, 1450
 1450 ITO       = ITO-1
      GO TO 75
 1500 WRITE (3,3000)
C
C     FORMAT STATEMENTS
C
```

```
 1001 FORMAT ( 11I5, 5F5.0)
 1002 FORMAT ( 2I5, 6F10.0, I5)
 1003 FORMAT ( 2I5, 7F10.0 )
 1004 FORMAT ( 2I4, 1X, 11F6.2)
 1005 FORMAT ( 8F10.2 )
 1007 FORMAT ( ' ' 34X I3, 3F20.2 )
 1008 FORMAT ( 7( I5, F5.0))
C
 2002 FORMAT ( 3I5, 6F10.2, I5 )
 2003 FORMAT ( 3I5, 7F10.2      )
C
 2004 FORMAT ( 3I4, 1X, 11F6.2 )
C
 2005 FORMAT  ('0' 4I5,(7F10.3))
C
 2007 FORMAT ( '1' 49X 'CALCULATED MIN- & MAX- FLOW DATA' /
     A          '0' 35X 'JJ' 12X ' RFLOW(JJ)' 11X 'MINRQ(JJ)' 11X
     B          'MAXRQ(JJ)' // )
C
 3000 FORMAT('1' 10X 'END OF JOB')
C
C
 3002 FORMAT ( '1' 60X 'STREAM DATA' /  0' 4X 'SECTION' 3X 'I-NODE' 3X
     A          'J-NODE' 6X 'DISTANCE' 9X 'AREA' 12X 'AA' 14X 'BB' 13X
     B          'CC' 13X 'DD' 8X 'TYPE' / ' ' 35X '(MILES)' 7X
     C          'SQ.MILES)' // (' ' 3I9, 6F15.3, I9))
C
 3003 FORMAT ( '1' 60X ' WASTE DATA' / '0' 5X 'NUMBER' 4X 'NODE' 5X
     A          'TYPE' 9X 'FLOW' 11X 'DEOX' 11X 'BOD' 13X 'DO' 12X 'TEMP'
     B          11X 'PHOS' 9X 'REMOVAL' /38X '(MGD)' 8X '(1/DAY)' 5X
     C          '(MG/L OR #/DAY)' 4X '(MG/L)' 8X '(DEG.C)' 9X '(MG/L)'
     D          10X '(%)' // (1H 3I9, 7F15.3))
C
 3004 FORMAT ( '1' 57X 'STREAM FLOW DATA' / '0' '   NUMBER  NODE   TYPE'
     A           '    MIN-FLOW  MAX-FLOW    BOD' 8X 'DO' 7X 'PHOS' 6X
     B          'DEOX' 6X 'TEMP     F-TEMP     F-DO     F-BOD      '
     C          'F-PHOS' / 27X '(CFS)     (CFS)     (MG/L)    (MG/L)'
     D          '     (MG/L)   (1/DAY)   (DEG.C)' // (' ' 3I7, 11F10.2) )
C
 3005 FORMAT ( '1', 6X 'NODE' 8X 'T' 10X 'FLOW' 9X 'DISTANCE' 10X 'BOD'
     A         11X 'TEMP' 11X 'SATDO' 11X 'DO' 12X 'PHOS' / 30X '(CFS)'
     B         9X '(MILES)' 8X '(MG/L)' 9X '(DEG.C)' 8X '(MG/L)' 9X
     C         '(MG/L)' 9X '(MG/L)' // (2I10, 7F15.2) )
C
 3006 FORMAT (  I10, 6F20.2)
C
```

```
 3007 FORMAT ( '1' 6X 'NODE' 14X 'FLOW' 16X 'DEOX' 16X 'REAIR' 13X
     A         'VELOCITY' 14X 'DEPTH' / 25X '(CFS)' 14X '(1/DAY)' 13X
     B         '(1/DAY)' 14X '(FEET)' )
C
 3008 FORMAT ( / ( I10, 5F20.2 ))
C
C
C
 3011 FORMAT ( '1' '  CONSTRAINT TOO LARGE - - - - JOB CANCELLED ')
C
 3012 FORMAT ( I5, 2F10.3 )
C
 3013 FORMAT ('1' 51X 'DYNAMIC PROGRAMMING BASIC DATA'//'0' 17X
     A        'TEST 1' 4X 'TEST 2' 4X 'TEST 3' 4X 'TEST 4' 4X 'TEST 5'
     B         5X 'ADD 1' 5X 'ADD 2' 5X 'ADD 3' 5X 'ADD 4' 5X 'ADD 5'//
     C        (14X 10F10.2))
C
 3014 FORMAT ('1' 53X 'INCREMENTAL FLOW TABLEAU' / '0' 59X
     A       'U-NODE ='I4/'0' 2X 'FLOW' 16X 'BOD' 17X 'DOD' 16X 'SAT-DO'
     B       15X 'DEAIR' 15X 'TEMP' 13X' COST' / 2X '(CFS)' 15X '(MG/L)'
     C       14X '(MG/L)' 14X '(MG/L)' 14X'(1/DAY)'12X '(DEG.C)' 11X
     D       '(ANNUAL)' // ( F8.2 , 6F20.2 ))
C
 3015 FORMAT ('1' 50X 'DYNAMIC PROGRAMMING TABLEAU' I3/'0' 59X
     A       'FOR NODE = ' I3 / 'OTOTAL FLOW' 3X 'FLOW AT ' I3, 4X
     B       'FLOW AT = ' I3, 8X 'BOD' 12X 'DOD' 10X 'SAT-DO' 9X
     C       'DEAIR' 10X 'TEMP' 11X 'COST' /'   (CFS)' 9X '(CFS)' 10X
     D       '(CFS)' 12X '(MG/L)' 9X '(MG/L)' 9X '(MG/L)' 8X '(1/DAY)'
     E        7X '(DEG.C)' 8X '(ANNUAL)' // ( F8.2, 8F15.2 ))
C
 3016 FORMAT ( '1' 6X 'NODE' 14X 'FLOW' 16X 'BOD' 17X 'DOD' 16X 'PHOS'
     A         17X 'TEMP' 16X 'DEOX' / 25X '(CFS)' 13X '(#/DAY)' 13X
     B         '(#/DAY)' 13X '(#/DAY)' 14X '(DEG.C)' 12X '(1/DAY)' // )
C
 3017 FORMAT ( 50H1 O-VALUES UNDERDIMENSIONED - - - - JOB CANCELLED )
 3050 FORMAT ('1' 58X 'INPUT DATA' /// 10X 'STREAM SEGEMENTS' 15X
     A        'WASTE DISCHARGES' 15X 'FLOW ADD POINTS' 17X
     B        'RESERVOIRS' // I20, 3I30)
 3060 FORMAT ('0'/ ' ' 3X 'FIRST NODE' 3X 'REAIR' 5X 'D-SETS' 4X'F-SETS'
     A         4X 'T-SETS' 4X 'I-BOD' 4X 'O-TYPE' 4X 'INC' 6X 'DELTA' 5X
     B        'REMBOD' 4X 'REMPHS' 2X 'D-FIRST NODE'// 7I10, 5F10.2 )
 3070 FORMAT ('1' 57X 'RESERVOIR DATA' // 13X 'NO.' 5X 'NODE' 5X
     A       'COST-INC' 5X 'T-INC' 2X 'T-ACRE-FT' 2X 'WO-ACRE-FT'
     B       2X 'T-COST' 4X 'WO-COST' 2X 'AVE-FLOW' 2X 'INCREASE-Q'
     C       // (4X, I11,I9,2I11,2X,2F10.0,1X,2F10.0,F9.0,F12.0))
C
```

```
 4001 FORMAT ( 3I10, F15.3, I10 )
C
 4008 FORMAT ( 2I5, 2F20.3)
 4010 FORMAT ('1' 60X 'ADDITIONAL DATA'//'0' 1X 'IT2' 3X 'S.S. TEMP.'
     A         3X 'IT3' 3X 'DO-CONSTR.' 3X 'IT4'  3X  'DEPTH FACT' 3X
     B         'IT5' 3X 'DECAY TEMP' 3X 'IT6' 3X 'DECAY PHOS' 3X 'IT7'
     C         3X 'S.S. PHOS.' 3X 'IT8' 3X 'DY EQ BOD.' //'0'
     D         2X, I1,  F11.2, 6%I8, F11.2<<
 4050 FORMAT ( 4I5,6F10.0)
C
 5001 FORMAT ('1' 54X 'MINIMUM   TREATMENT' // ( 62X F5.2 ))
C
C
 6000 FORMAT ( 4I5 // ( 5F15.2) )
 8000 FORMAT ( 5X, F5.0, 7F10.0 )
 8005 FORMAT (8X, 12F6.0)
 8010 FORMAT ( 'ERROR 1260' )
C
      CALL TIMED
 9999 STOP
      END
      FUNCTION QSATDO(TEMP)
      QSATDO    =  14.652 - (0.41022    * TEMP)
     A                    + (.007991    * TEMP * TEMP)
     B                    - (.77774E-4 * TEMP * TEMP * TEMP)
      RETURN
      END
```

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KEY TO ABBREVIATIONS

ASCE	American Society of Civil Engineers
ASCE-HY	American Society of Civil Engineers, Hydrology Division
ASCE-SA	American Society of Civil Engineers, Sanitary Division
JWPCF	Journal of Water Pollution Control Federation
SIW	Sewage and Industrial Waste
SWJ	Sewage Works Journal
WRR	Water Resources Research
WSW	Water and Sewage Works